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Social Internet of Things (SIoT): Foundations, thrust areas, systematic review and future directions

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ABSTRACT

Internet of Things (IoT) paradigm connects physical world and cyberspace *via* physical objects and facilitate the development of smart applications and infrastructures. A physical object is the basic constituent of IoT, often called as *smart object*, that interact with other objects and possess the information processing abilities. The smart objects when deployed in the real world, collect information from the surrounding environment and this is abstracted as a *service*. IoT has established a universe where humans are provided smart data services by the fusion of physical objects and information networks. This approach has been extended to include social networking aspects in the IoT that autonomously build social relationships to discover objects and their services *viz*; Social Internet of Things (SIoT). SIoT enhances information sharing, supports new applications and provide a reliable and trustworthy networking solutions utilizing the social network of *friend* objects. In this paper, we present the fundamentals of SIoT, identify thrust areas of it (as service discovery and composition, network navigability, relationship management, and trustworthiness management) and present several prerequisites, challenges and use case scenarios based on them. State-of-the-art research publications are reviewed on service discovery, relationship management, service composition and trust management constituents of the SIoT environment. Finally, we identify and discuss the future research directions that serves as a reference for the next generation discovery techniques to improve service provisioning, find the optimal solution for the link selection in the SIoT structure, develop large scale platforms and provide a smart mechanism for trust evaluation.

Contents

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1. Introduction

With the burgeoning technological developments in nanotechnology and embedded computing, information and communications technology today has spread its vision to connect the physical world with the digital space. Physical objects surrounding us are being embedded with computing technologies (such as sensors, actuators, communication devices, etc.,) so as to give them a digital imprint and thus enabling them to perceive the surrounding environment and understand their role in the context of the present situation. Given this ability, the physical object is able to interact with other objects in its vicinity to coordinate and complete the given task to achieve the desired results. To this end, Internet of Things (IoT) paradigm has evolved that connects the physical objects to the Internet and enables creation of applications that helps to solve day-to-day activities effectively and efficiently [1]. IoT is defined as a system of interrelated computing devices, mechanical and digital machines, objects, animals, or people that are provided with unique identifiers, and are able to collect, analyse and exchange data without explicit intervention [2]. Each such object in IoT system offers a particular service through which persuasive applications are designed. The ultimate purpose of IoT is to create more time and better living for mankind, where the objects surrounding us understand our desires, requirements and interests and act accordingly without taking any external instructions [3,4].

Though IoT is of great benefit to the society, it poses a plethora of challenges for the designers and developers. Heterogeneity is a primary concern where IoT devices are of varying nature at various levels from different perspectives *viz.* standards, communication protocols, deployment features, etc. These characteristic attributes impede the development of a common solution model for application development unless appropriate communication paradigms among the heterogeneous devices are identified. Scalability is another major issue where the number of devices that are getting connected to the IoT network is growing at a tremendous rate. These devices offer numerous services and collect huge volumes of data at rapid pace. Several such challenges are difficult to address given the dynamic nature of the IoT system.

Our society is also heterogeneous, dynamic, and complex in nature but there exists social relationships among us where we form communities based on several factors (such as common interests, influence, needs, etc.,). We interact and collaborate among the members of the community to solve any complex problem. This concept of social network can be incorporated in IoT to successfully address the challenges faced by an IoT ecosystem. Adopting these social features for the IoT paradigm has given birth to a new concept of social network of smart objects, services or both, and named as Social Internet of Things (SIoT), that definitely suffice the needs of users, developers and designers [5–8]. With the increasing penetration level of the IoT devices in our society, today we have myriad range of choices to select applications or services and thus our interactions with these devices will also be at a large number. Relationships can be established among these interacting components i.e., humans and physical objects and between the physical object themselves to form social networks.

Converging the social networking concepts with the IoT offers several benefits. First, the SIoT network structure can be formed as needed to ensure efficient navigability among the components based on several social aspects (like co-located, similar characters, etc.,) so that the detection of services and object is done effectively that aid in solution composition for complex tasks. Second, scalability is ensured as in social networks through collaboration. Third, a level of trustworthiness can be established for leveraging the degree of interaction between objects that are friends or friends of the friends in the SIoT [5]. The social object builds a relationship only with the trustworthy objects. These objects offers the desired services by independently interacting with other objects that have established good relationships. Finally, models developed to analyse social networks may be reused to resolve issues related to IoT.

In 2001, Holmquist et al., [9] were the first to put forward the concept of socialization among the objects of an IoT system. The significant idea behind SIoT is that, objects with identical profiles and features are able to share solutions to resolve problems encountered by other objects i.e., their interacting partners. There are experimental proofs that a wide range of connected people in a social network ensure precise results to complex issues as compared to a single person [10]. In an IoT network, objects have the ability to observe and listen to each other, while in an SIoT system they socialize with other components of the network to achieve better results for complex problems through collaboration and mutual cooperation [11].

Allied technologies such as ontologies [12], machine learning [13], commonsense reasoning [14], deep learning [15], deep multimodal learning [16], and human–computer interfaces [17], among the many are increasingly contributing to the development of SIoT. In the recent past, several reviews are conducted on trust management in SIoT [18, 19] while the concepts like service discovery, relationship management, service composition are not addressed in the SIoT settings. In this paper, we provide deeper perspectives on concepts, relationship types and different thrust areas of the SIoT (service discovery and composition, network navigability, relationship management, and trustworthiness management). The contributions of the paper is as follows:

1. We provide a holistic view on the fundamentals of SIoT domain. Different viewpoints of SIoT are summarized based on various types of relationships that occur in a SIoT system, and we also discuss in detailed the SIoT thrust areas.
2. We have delineated and categorized numerous prerequisites and challenges that arise in SIoT according to the thrust areas where they play a crucial role. The paper also describes several use case scenarios that are modelled according to the thrust areas.
3. We describe in-depth several techniques through which relationships of a SIoT application can be created and managed. These techniques guides the developers, researchers and early adaptors to provide effective solutions for relationship creation and management for different thrust areas of the SIoT. For each of the technique, we first describe its concept and then illustrate its work flow through an example and figure.
4. We have reviewed research publications that provide solutions to different problems of thrust areas of SIoT. For each of the thrust areas, we first provide an overview and then propose our taxonomy to classify the state-of-the-art works followed by analysis of each research publication along with their advantages and disadvantages.
5. The paper summarizes the existing SIoT platforms that offer solutions to design and implement an SIoT application. We describe the research publications that address numerous challenges of cyber world by incorporating social phenomenon into the IoT domain to overcome the present drawbacks. This discussion is useful for the readers to develop a thorough understanding of the present state-of-the-art techniques that address as the challenges of bare-IoT system by incorporating certain social features.

The rest of the paper is organized as follows. Section 2 presents tutorial on SIoT, its subsections covers different viewpoints of SIoT, various types of SIoT relationships, prerequisites and challenges, use case scenarios, and SIoT relationship creation and management respectively. Section 3 explains the components of the discovery system, classification of discovery techniques and a review of service discovery and service composition schemes, Section 4 contains design strategy for network link selection and a review of research efforts in network navigability and relationship management. Section 5 describes the trust management and a review of research efforts with reference to SIoT. Section 6 presents the review of various SIoT platforms. Section 7 highlights the future research directions for the SIoT. Finally, conclusions are presented in Section 8.

2. SIoT concepts

This section provides the fundamentals of SIoT domain. Section 2.1 describes different viewpoints of the SIoT system from definition and architectural perspectives. It also discusses various types of relationships that occur in a SIoT system along with a detailed discussion on the SIoT thrust areas based on which the works are reviewed in Sections 3–5. In Section 2.2 we delineate and categorize numerous prerequisites and challenges according to the thrust areas where they play a crucial role. Section 2.3 illustrates several SIoT applications that are modelled according to the thrust areas, and in Section 2.4 we provide in-depth description of different techniques through which relationships of a SIoT application can be created and managed.

2.1. SIoT paradigm

In the last couple of years, the concept of applying social networking aspects to an IoT ecosystem has received unprecedented amount of attention. For example, Quick Response (QR) code on books and business cards constitutes to a simple SIoT systems. QR code is a two dimensional code that is printed on physical objects and can be scanned and read by a smart phone or a digital scanner to transfer information. In case of books, the code can direct the readers to additional references like YouTube links and web-blogs etc., while in business cards the contact details can be digitally transferred to hand held electronic devices like smart phones, tablets and watches. Here, there exists a social relationship between the physical objects, digital space and user (say ownership of devices). This social relationship between human–things and things–things is a method that has now evolved as SIoT [20]. The SIoT combines IoT and social networks where every object can establish social relationships with other objects independently with respect to the heuristics set by the owner object.

Fig. 1 illustrates such an amalgamation between the physical objects, digital space and users. The physical world contains several real world objects that are embedded with sensing, actuating, processing and networking capabilities. These objects are fundamental constituents of an IoT application and offer some kind of services that are utilized by humans and other objects to accomplish day-to-day activities. There can be social network at various level and of diverse degrees between these components. Humans form communities among themselves based on several factors like common goals, interest, friendship etc., while they are also bound to the physical object through relationships such as usage, ownership, etc. Physical objects also establish relationships among themselves based on characteristic features like interaction level, location, etc. The SIoT is intended to manage trillions of things when facing the problem of information and service discovery and it is not meant for the sensing and networking in the IoT. In addition, mainly through service discovery and composition, it aims to lay the ground for autonomous interaction between the objects to benefit the human user [21].

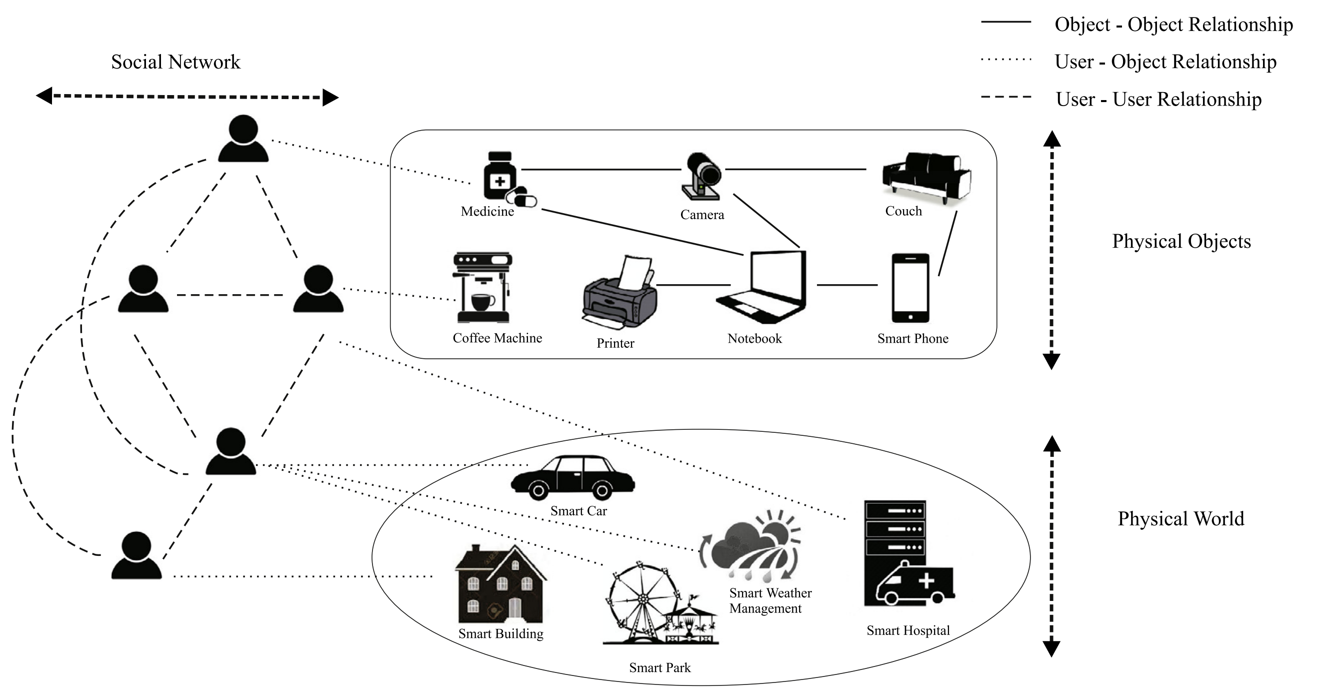

Fig. 1. Components of the Social Internet of Things.

2.1.1. SIoT architecture

Several attempts have been made by the researchers to develop an architecture for the SIoT system. Some of the works that describe such an architecture to integrate social aspects with the IoT networks are described in the following.

Kosmatos et al., [22] proposed an unified architectural model for the IoT, by integrating Radio Frequency Identification (RFIDs) tags and smart objects by exploring social features of the objects. The objects manage to associate with the community of objects, employed to create a social network and involve it in a suitable synergistic activities. However, it falls short on implementation. Ortiz et al., [6] proposed a generic SIoT architecture that allows a connection to the ubiquitous computing environments, by combining humans, devices and services. In this integrated architecture, the Internet of things enables thing-to-thing interaction whereas the social networks permits human-to-thing interaction. Internet of Things and the Social Networks are two concepts that are not disparate but work together to fulfil the interaction between things–things and humans–things in a cooperative manner. The social driven method enhances the service discovery, service selection, service composition and the data delivered by distributed objects accessing the real world through sensors, tags etc.

Voutyras et al., [23] proposed another architecture for SIoT by introducing the technique of Virtual Entities (VEs). VEs are equivalents of the physical world smart objects in the cyber world and have been integrated to real-virtual world. VEs obtain the information of the instances by accessing sensor readings and influence their surrounding area by performing physical activities choosing actuators through IoT-services. In addition, the VEs are activated with an inner logic to achieve their personal objectives. A multitude of VEs can create groups, referred to as Groups of Virtual Entities (GVEs).

Further, Voutyras et al., [24] developed an SIoT architecture using the principles of relational model. The Social Network Analysis (SNA) owns the responsibility of determining nearby and overall patterns and for finding prominent entities with the evaluation of network characteristics. The design includes four primary elements namely, the Friends Management (FM) element, Profiling and Policy Management (PPM) element, Social Monitoring (SM), and Social Analysis (SA) element. The interaction and social relationship between Virtual Entities are maintained by presenting these elements in the COSMOS management framework [25].

2.1.2. SIoT perspectives

Applying social relations to the IoT systems have attracted several research attentions. Some of the works focus on human–object relationships while others consider only the object–object relationships. While others make use of existing social networking platforms and integrate it with the IoT system. In the following, we review such articles:

Atzori et al., [7] reviewed the leading possibilities originated from the assimilation of social networking principles into the IoTs. The social participation of the objects comprising IoTs is defined in three different stages. In the initial stage, using the social networks of humans objects post details about their state. In the next stage, objects communicate with other objects and people in social networks. In the last stage, objects build a communication network by socially interacting with each other. Gou et al., [26] proposed a concept, named opportunistic IoT by analysing the tightly linked relationships among people and opportunistic connectivity of intelligent objects. Sensing and monitoring the behaviour of the humans, the devices associated with the IoT attempt to offer the Internet of Things with user awareness, ambient awareness and social awareness.

Mendes [27] recommends a technique in which objects are able to take part in the interactions that were reserved only to the humans in the past. It showcased a user-centric relationships, where augmented objects are networked to help with the interaction between humans and their social and physical surroundings. This is achieved by means of software embedded in portable objects with increased sensitive functionalities and make the objects to establish a dynamic networking framework using the information available with the object itself as well as that which is distributed. Doddy et al., [28] presented an idea of applying the reality mining technique to the Internet of things, which has been developed to comprehend the human behaviour and relationships, thus allowing the interaction among smart objects.

Ding et al., [29] worked on the development of a platform to cluster the Internet, IoT objects and social networks to analyse the behaviour of objects and people in the form of data. If things are included along with people into the network built upon the IoT, the social networks can be established. This social network needs to explore the relationships and evolution of the objects in the IoT, thus blending IoT and social networks. Guinard et al., [30] discussed about integrating the IoT and existing social networks for application development using

Table 1
SIoT research trends.

Research contribution	Arch	OO relat.	UO relat.	SN
Ding et al., [29]			✓	✓
Guinard et al., [30]			✓	✓
Baqer [31]		✓		✓
Kranz et al., [32]		✓		✓
Mendes [27]		✓	✓	
Kosmatos et al., [22]	✓	✓		
Gou et al. [26]			✓	
Doddy et al., [28]		✓	✓	
Ortiz et al., [6]	✓	✓	✓	
Voutyras et al., [23]	✓	✓		

Arch — Architecture, OO Relat. — Object–Object Relat, UO Relat. — User–Object Relationship, SN — Social Network

web patterns whereby the established real world objects and social networks could be reused or recombined to create new applications. Using the existing social networks, an individual shares things and also recommends or reviews the services provided by smart things with his/her friends. The existing human social media websites like Twitter, Facebook, LinkedIn, etc. as a framework for object detection, promotions, and access have been utilized. This violates the perspective of IoT, where the objects without human intervention need to socialize to offer value-added solutions to the people.

Baqer [31] presented a model that employs social network as a medium to collect information from distributed sensors and share the physical information to improve the management of sensor networks. Kranz et al., [32] have demonstrated to enable physical objects to exchange images, remarks, and sensor information *via* social networks. The effects of the term *socio-technical networks* in the IoT framework for a remarkable instances of applications have been illustrated. However, it neither addresses possible measures to set up social relationships among objects nor it provides a feasible architecture for the social IoT. Table 1 summarizes the above articles from architectural and relationship type viewpoints.

2.1.3. SIoT relationship types

Relationships in a SIoT system can be classified into two types as (i) User-Object Relationship (UO Relationship), where there exists some form of association between the user and physical object, and (ii) Object-Object Relationship (OO Relationship), where the physical objects are bound to each other through some relation. To develop a SIoT application the type of relationships to consider plays a very crucial role and it depends on the application domain. Atzori et al., [5] have described several applications of the SIoT by exploiting different types of relationships among the objects. Fig. 2 illustrates some of the applications that can be developed using these relationships. In the following, we describe the type of relationships that exist in an SIoT environment.

1. *UO Relationship*:
   - (i) *OOR* — Ownership Object Relationship where the objects belong to the same user (smart phones, iPad etc. belonging to a user),
   - (ii) *SOR* — Social Object Relationship where objects come into contact because of social relationships (relationship between objects and sensors belonging to friends in the social network, for example, interchange of phone numbers amongst friends automatically through the system).
   - (iii) *SIBOR* — Sibling Object Relationship is established among objects that belong to a family member or a group of friends [33].
   - (iv) *GSTOR* — Guest Object Relationship is formed among objects owned by the users in the guest role, for instance, when a person spends time socially at friends place and takes the liberty as a guest.
2. *OO Relationship*:
   - (i) *POR* — Parental Object Relationship describes the relationships among similar objects unchanged by time (example microwave ovens built by the same manufacturer, period etc.),
   - (ii) *CLOR* — Co-Location Object Relationship determined where objects reside at the same place (sensors, tags on appliances that reside in the same place to offer service, for example automation in a home or office),
   - (iii) *CWOR* — Co-Work Object Relationship determined by objects that work together to provide service for a common IoT application (sensors, alarms in a home and *app* on smart phone providing a burglar alarm system that can be monitored over the Internet),
   - (iv) *GOR* — Guardian Object Relationship where vehicles On-Board Units (OBU) turn into a child in association to the super objects of Road Side Units (RSU), thus giving a special signification to a novel hierarchical relationship [34].
   - (v) *STGOR* — Stranger Object Relationship exists among objects that encounter the existence of each other in the public surroundings or on the go.
   - (vi) *SVOR* — Service Object Relationship is formed between objects that fulfil the service request by coordinating the same service composition. Every object in the network autonomously establishes various types of relationships and uses the resulting links for network navigation.

2.1.4. SIoT thrust areas

SIoT enables creation of enthralling applications which facilitates interaction between humans and physical objects through the digital space thereby enabling creation of shared community that operates towards the betterment of the society. There are several areas of the SIoT paradigm that require attention from the research, industrial and academic community, which we denote as *Thrust Areas of SIoT,* to address the challenges and open issues and develop appealing applications that are widely accepted. These areas are depicted in Fig. 3 and explained in the following:

- (i) *Service Discovery and Composition*: Service discovery is a fundamental component, finds what service is available from the objects similar to the humans seeking information and services on the social networks. Service composition enables interactions between objects where the services are identified by the service discovery component.
- (ii) *Network Navigability*: Every object in the network autonomously establishes various types of relationships and uses the resulting links to navigate the network. This shortens the average path length between all the pairs of the objects and make the object and service discovery process more effective and scalable.
- (iii) *Trustworthiness Management*: Ensures reliable interaction between objects thus reducing the exposure to malicious objects.
- (iv) *Relationship Management*: Embeds intelligence into the objects so that they can realize friends and foes and start a friendship, update the status as and when changes occur and terminate the relationship.

2.2. Prerequisites and challenges

SIoT system are encountered with a number of challenges that scales down their performance quality. To improve their usability and applicability across varied SIoT application domains they need to be support certain prerequisites. In this subsection, we discuss some of the prerequisites and challenges for developing a comprehensive and robust SIoT system.

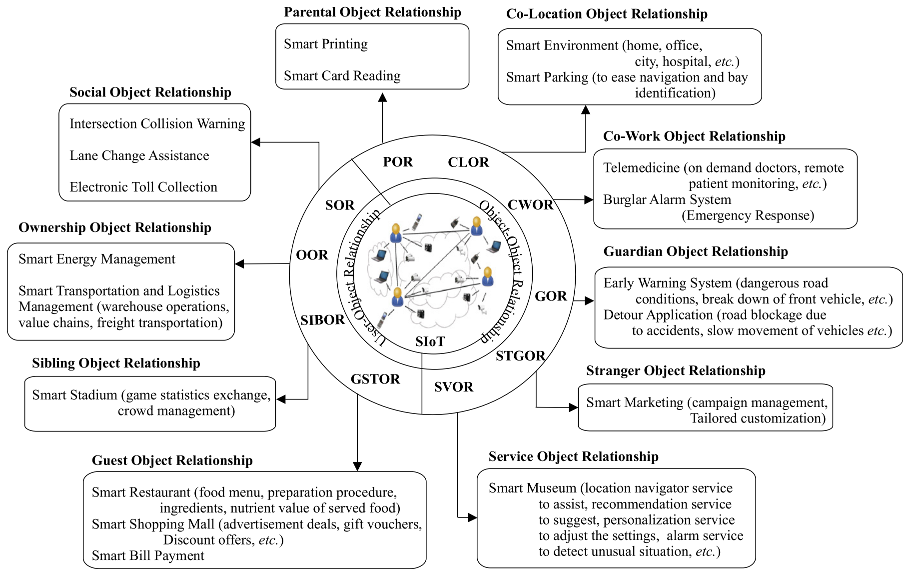

Fig. 2. SIoT applications under different types of relationships.

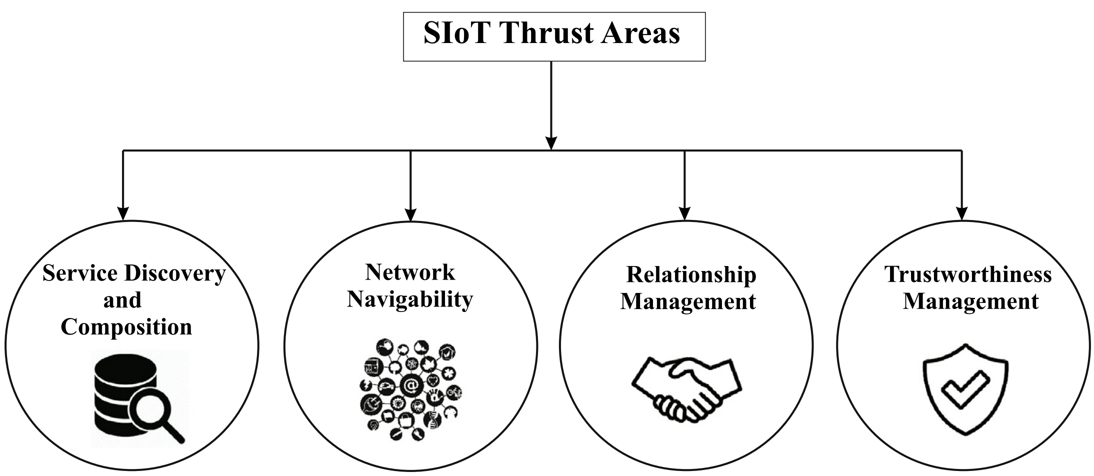

Fig. 3. Thrust areas of the SIoT.

1. *Prerequisites:* SIoT applications must incorporate the following prerequisites to provide improved solutions.
   (i) *Personalization:* Discovery system must necessarily calibrate the results to match the preferences of the user.
   (ii) *Multi-Attribute Request:* Discovery system should support request containing more than one attribute (*e.g.*, location and type)
   (iii) *Request Range:* Discovery system should support the request that consists of upper and lower bound.
   (iv) *Recommendation:* Discovery system must provide recommendations of services if it fails to provide the required service.
   (v) *Interactive and Responsive Interface:* Discovery system should provide user friendly interface and enhanced results such as object status, latest updates, generated events *etc.*
   (vi) *Multicast Feature and Classified Query Results:* Discovery system should provide multiple replies for a single request and search results must be categorized into structured class based on request.
   (vii) *Minimum Latency:* Waiting time should be at the lowest during different stages of discovery algorithm.
   (viii) *Energy Management:* Discovery approaches must account for the energy consumption in the objects.
   (ix) *Inter-Connectivity:* Discovery system must be automatically updated with IoT objects current status.
   (x) *Accuracy:* Search result must accurately match the query request and provide the most relevant results.
   (xi) *Privacy:* Search result must conceal the most sensitive information of the IoT objects.
   (xii) *Security:* Discovery approaches must account for the security level as per the users and objects specification.
   (xiii) *Trustworthy:* List only the trustworthy results for the users.
2. *Challenges:* SIoT environment faces the following challenges.

(i) *Scalability:* Discovery system must manage the large number of objects connected to the SIoT.
(ii) *Mobility:* Discovery system must handle the objects that changes its location more frequently.
(iii) *Dynamicity:* Discovery system should deal with constant joining and leaving the network that results with change in the network topology.
(iv) *Opportunistic Existence:* Discovery system should handle dynamic interaction status of the objects with the SIoT network.
(v) *Heterogeneity:* Discovery system should take into consideration wide variety of objects, multiple communication protocols and variety of applications.
(vi) *Interoperability:* Discovery system must function among heterogeneous data sources at different levels and platforms.
(vii) *Adaptability:* Trust protocols designed for discovery system must adapt to the changing environmental conditions.
(viii) *Survivability:* Trust management protocols designed for discovery system must sustain to malicious attacks.
(ix) *Resiliency:* Discovery system should be resilient to attacks and establish a secure communication channel.
(x) *Standardization:* Discovery system should be realized with widely accepted standard communication protocols.

Table 2 lists and describes the prerequisites to improve the functionalities of the thrust areas along with the challenges that need to be addressed by them in SIoT domain.

2.3. Use case scenarios

This subsection describes the applicability of the thrust areas across different disciplines in SIoT applications along with the use case scenarios. (As listed in Table 3).

1. Service Discovery

(i) *Location based Discovery:* Discovery system in the E-Health domain [35] provides updated information about the drugs availability in the nearby pharmacies. The discovery system must contact the doctors system and get a new drug prescription and also recommend the drugs that are expected to have the same clinical effect if the prescribed drugs are unavailable.
(ii) *Time based Discovery:* Discovery system in the smart airport domain [36] provides assistance to the passengers to locate their baggage drop-off point, updates about change in the boarding gate, detects if the lighting condition is suitable for reading at the boarding gate, figure out the number of passengers who are currently boarding *etc.*.
(iii) *Spatio-Temporal based:* Discovery system in the smart parking domain [37] helps the users to automatically locate a parking space with least cost at a specific location and at a given time instance.
(iv) *Encounter History based:* Discovery system in the Intelligent Transportation Systems (ITS) domain [38] recommends the user in the heavily traffic area to find optimal route. In such an application, the candidate object contacts the target object that are travelling on different routes or miles away based on the preferences and long term social links with other objects that shared information in the past.
(v) *Mobility pattern based:* Discovery system in Intelligent information domain traces the regular movement trajectories [39] of user to provide information about the current situations such as *train is delayed, coffee shop is closed, no cash in ATM etc*.

2. Network Navigability

(i) *Objective Friendship:* A SIoT system in Smart Home domain is able to understand the user behaviour through situational awareness techniques and provides him nearest optimal service based on his preferences.
(ii) *Object Similarity:* Recommendation system in a Smart Stadium domain advocates a spectator to choose a social community based on the team which is supports to in the present game thereby establishing a temporary social network where users can share their emotions and game related information.

3. Trustworthiness Management: A taxi booking service in an ITS application takes into account the trust factor of not only the travel agency but also the driver to establish a dynamic relationship between the user, driver and taxi. This relationship will not only ensure safety of the passengers but also provides satisfactory performance ratings to the taxi service provider and driver.

2.4. SIoT relationship creation and management

The application development process for a given domain of the IoT involving social aspects requires modelling of the different types of relationships that arise in it. Due to the complexity of social structure that incorporates vivid relationships between the various components of the SIoT, it is a demanding task to model the social aspects for a given smart environment. However, the relationship design task can be simplified by structuring the relationships according to numerous design strategies as discussed below:

2.4.1. Definition of relationship through inference rules

Inference rules stems from predicate logic and helps to establish a well defined relationship among the components of a SIoT system. They are in the form of *if-then* rules that have two parts. An antecedent part, that establishes the logical validity of the relationship and a consequent part, that gives credibility to the relationships. Having a rigid definition of the different types of relationships that arise in an SIoT domain enables the developer and implementer to focus on the pressing issue of the application rather than socializing the IoT objects and users. Through inference based relationship management system a robust SIoT application can be developed that suffices the needs of all the thrust areas of the SIoT. However, a rigid knowledge on the operation domain is required to design such a system.

Table 4 lists an example set of inference rules. These rules are designed based on the definition of the relationships. An SIoT application

Table 2
List of prerequisites and challenges.

Type	Thrust areas	Criteria	Description
Prerequisites	Service discovery	Multi-attribute requests	Search queries containing more than one query constraints (e.g., location and type).
		Request range	Discovering objects based on request specifying the upper and lower limits.
		Accuracy	Search results must accurately match the query request and deliver the most relevant results.
		Interactive and responsive interface	Provide user-friendly interface to interact with objects and other users.
		Multicast feature and classified query results	A single discovery request must fetch multiple replies and the discovered results must be categorized into structured class based on the search request.
	Network navigability	Minimum latency	Reduce waiting time of the mobile SIoT objects during different stages of object discovery algorithm
		Energy Management	Energy should be conserved and managed efficiently in the IoT resources.
		Inter-connectivity	User need not check the status of the surrounding IoT objects any more, it must automatically update its current status to the user.
	Trustworthiness management	Recommendation	Recommendation of other services must be performed in case if the service provider fails to provide the requested service.
		Personalization	Discovered results should be calibrated to match the preferences of the user.
		Privacy	Search results must conceal the sensitive information and interaction among IoT objects.
		Security	As per the IoT objects and users specification, the discovery techniques and interaction must account for the security level.
		Trustworthy	Manage trustworthiness communication between objects and list only the trustworthy results to the user.
Challenges	Network navigability	Scalability	The large amount of objects connecting the IoT must be handled.
		Mobility	IoT objects changes its location more frequently.
		Dynamicity	IoT objects are constantly joining or leaving network resulting with change in network topology.
		Opportunistic existence	Dynamic interaction status among IoT objects in the network of smart objects.
	Relationship management	Heterogeneity	Wide variety of objects, multiple communication protocols, variety of applications.
		Interoperability	The ability to operate among heterogeneous data sources to communicate with each other at different data level and platforms.
		Standardization	Widely accepted standard communication protocols.
	Trustworthiness management	Adaptability	Designed trust protocols must adapt to the changing environmental conditions.
		Survivability	Trust management protocols must sustain malicious attacks.
		Resiliency	Resilient to trust related attacks and establish secure interaction.

Table 3
Applicability of thrust areas across different SIoT applications.

Thrust areas	Design strategies	Applicability	SIoT applications	Use case scenario
Service discovery	Location based	For applications that require to find services at absolute location or relative to some other object.	E-Health System	Check for the availability of drugs in the nearby pharmacies by means of co-location relationships.
	Time based	For applications that need to discover services that are active at particular time or period.	Smart Airport	Detects the number of passengers currently boarding.
	Spatio-Temporal based	For applications that require to find services at a particular location and time.	Smart Parking	Search for a parking lot with lower cost at a specific location and at a given time instance.
	Encounter History based	For applications that provide information based on long term social links between IoT objects that shared information in the past.	Intelligent Driving System	Computing the best path by avoiding unexpected congestion points.
	Mobility Pattern based	For applications that provide information utilizing the mobile trajectories of the users.	Smart Information System	Traces the regular movement trajectories of user to provide information about the current situation.
Network navigability	Object Friendship	For applications that have to handle diverse set of physical objects that perform several tasks simultaneously.	Smart Home	Route a unforeseen request dynamically to the nearest optimal node based on situational awareness.
	Object similarity	For applications that require to establish temporal community based on some common preferences or user behaviour.	Smart Stadium	Setup a temporary social community between supporters of same team and share the game statistics instantaneously among them.
Trustworthiness management	–	For applications that require to isolate the misbehaving objects from the SIoT network and dynamically constructing the social relationship between benevolent objects.	Augmented Travel Assistance	Formulate service work-flow plan for a service request and select the best service provider to fulfil the request.

can create rules based on the specific behaviours of the user/physical objects, situation intelligence, contextual conditions, etc. These rules are created during the design phase of the applications and are stored in repositories for future retrieval. However, there is a need for future works to develop mechanisms where the inference rules are updated dynamically based on the structure of the social aspects of the IoT network. In the recent past, several such rule based SIoT models are developed *viz.*, University and Car polling [40], Trust Management [41] and Smart Building [42] applications for relationship creation and management.

Table 4
An example set of inference rules for SIoT.

Object relationship types	Inference rules
Parental Object Relationship (POR)	**if** (O_y.*creator* ∧ O_x.*creator* :== SameManufacturer) ∨ (O_y.*model* ∧ O_x.*model* :== SameModel) then Object O_x has POR with Object O_y
Co-Location Object Relationship (CLOR)	**if** (O_x.*absoluteLocation* ∧ O_y.*absoluteLocation* :== SameLocation) ∨ (O_x.*relativeLocation* ∧ O_y.*relativeLocation* :== SurroundingArea) **then** Object O_x has CLOR with Object O_y
Co-Work Object Relationship (CWOR)	**if** (O_x and O_y offer same service) **then** Object O_x has CWOR with Object O_y
Ownership Object Relationship (OOR)	**if** (O_x and O_y have same owner) **then** Object O_x has OOR with Object O_y
Social Object Relationship (SOR)	**if** (O_x and O_y belong to same community) **then** Object O_x has SOR with Object O_y

2.4.2. Description of relationship through ontology

Semantic technologies leverages sophisticated domain knowledge about the social aspects and enables the interactions among users and objects based on the defined rules on object relationships. Ontological model is one such technique where different components of a SIoT application are related to one other hierarchically. It is also possible to define attributes of the relationships in such a model so as to envisage the degree and constraints among them. Through such a model a rigid foundation is laid above which a solution platform can be built to address issues related to trust management, navigability, and service discovery. Conceptualization of user, object and their relationships into ontological structures are extremely advantageous. For example, (i) new kinds of relationships among the network of users and objects can be discovered through inference engines (ii) consistency of the association between the components of the network can be checked, *etc.* In such a model, each object and user for a given domain is defined in terms of a ontology class and relationship is established between them through ontological properties. There are two such properties, data properties signify the attributes of the components while object properties establish relationship between them [43].

To model the user-object and object–object relationships described in Section 2.1, an example ontological model for interpreting object relationships can be designed as depicted in the Fig. 4. In this ontology, data properties represents the user and physical object attributes (denoted by dashed oval) and the object properties describe the links between them (denoted by solid oval). The data properties are: *<:hasIdentification>* indicates a unique number, Electronic Product Code (EPC) encoded on RFID tag, IMEI for International Mobile Equipment Identity *etc.* can be used for this purpose, *<:hasSocialFriendsList>* tabulates the friends list an object has, the number of friends an object is associated with is indicated by *<:hasNumberOfFriends>* property. The object properties are: *<:hasOwner>* gives description of the user/owner of the object, *<:addFriend>* adds another object to its friendlist, *<:deleteFriend>* removes one object from the social relationship list, *<:hasRelationship>* denotes the various relationships between two instances of the object class, *<:isCurrentlyIn>* discovers the current check-in geolocation of the object. Ontologies proposed in [44–47] are quite useful in this context.

2.4.3. Predicting relationship through machine learning/artificial intelligence techniques

Although defining and structuring the relationships of a SIoT system *apriori* gives rigidity and robustness to the application, its a tedious task and suffers from scalability issues due to the presence of a large number of users and physical objects. Also, the dynamic nature of the relationship between the entities of the SIoT pose a challenge. To this end, predictive models can be used to extract dynamic associations between the components of a SIoT system. Machine learning algorithms and artificial intelligence techniques plays a pivotal role here to deduce degree of association among the several actors of the SIoT based on their role, behaviour, pattern, needs etc.

Candidate methods are to be devised through use of cognitive techniques to handle relationships, manage activities of user and incorporate user behaviour and preferences. Kasnesis et al., [48] describe two types of methods to predict relationships among the components of the SIoT as deductive and abductive.

(i) *Deductive Methods:* These techniques are used when domain oriented interactions among the users and objects are to be extracted. For example, in a SIoT application designed for Smart Home domain that offers service discovery, deductive techniques can be used to mine relationships between the residents and appliances based on their interaction level.

(ii) *Abductive Methods:* These techniques are useful to deduce and manage relationships that are incomplete, temporary and depend on the subjective characteristics of the interacting components. For example, an application designed for thrust management has to extract relationships based on user preferences.

3. Service discovery and composition

3.1. An overview of service discovery process in SIoT

Service discovery is targeted at discovering the objects that offer an appropriate service for the benefit of the users. In IoT, locating objects, information and services is a critical issue particularly in real-time environments [49]. This section describes the basic components and design strategies of the service discovery process in SIoT. A discovery function is alike for humans and objects in SIoT. SIoT establishes social structures among objects and people that intend to provide services. When users/objects sends a platform specific/independent request to discover objects (which are basically considered as the service provider) through Application Programming Interfaces (APIs), the request is matched with the available services that exist in the exact or near to their locations and that meets their preferences and history of interactions. A list of all the relevant objects/services that exactly match their requisites and meet their quality of service level is returned to the requester. Algorithm 1 outlines the steps for object/service discovery process in SIoT that consists of service request, fetching facts, service matching, service filtering and service list.

Algorithm 1: Service Request Resolution Process in SIoT

1. *Service Request:* User/Object sends a request to discover smart services and objects.
2. *Fetching facts in Request:* Preprocess the discovery request to fetch the facts like location, service type *etc.* by the Natural Language Processor.
3. *Service Matching:* Search for services of matching type from Service Repository.
4. *Service Filtering and Ranking:* Eliminates the irrelevant services and ranks the services based on rating, authorization, trust *etc.*
5. *Service List:* Returns the ranked list of relevant services that matches the objects/users needs.

3.2. Basic components of discovery system

A discovery system is designed to locate objects, information and services that matches the discovery request. The basic components of SIoT discovery system is detailed as follows:

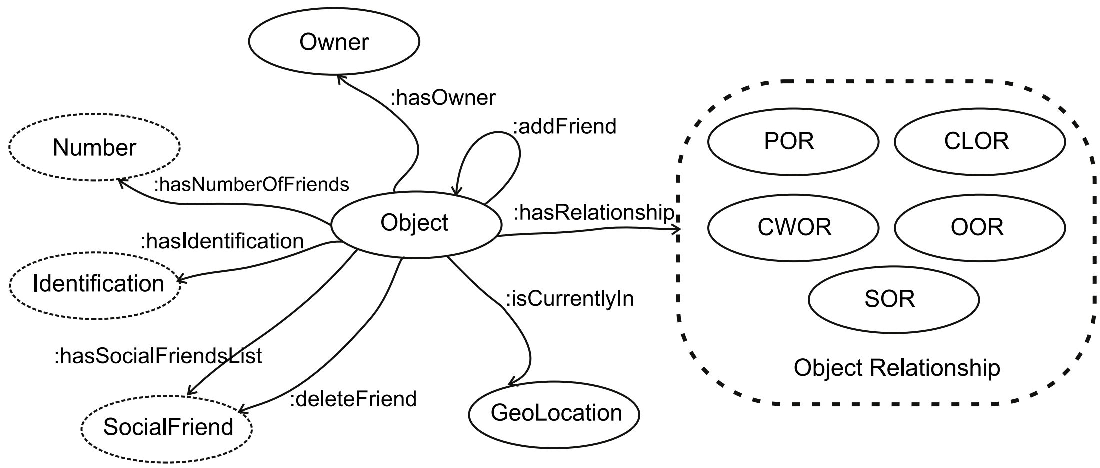

Fig. 4. Ontological model interpreting object relationship.

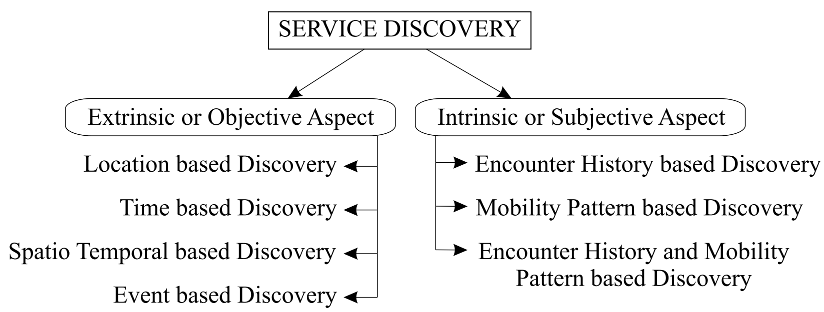

Fig. 5. Taxonomy for SIoT based service discovery mechanisms.

3.2.1. Smart objects

The physical objects embedded with RFID Tags, sensors, actuators, communicating devices, *etc.* are the smart objects, that collects information, processes, and interacts with the other smart objects.

3.2.2. Object relationship

Discovery system establishes various relationships between smart objects and autonomously discovers a target object that provides the required service.

3.2.3. Discovery area

Discovery area is a collection of smart objects and their related data items over which discovery algorithm finds the matching object based on some prerequisites [50]. Smart objects form a social structure using Friend of a Friend (FOAF) relationship to reduce the size of discovery area [51].

3.3. A classification for discovery methods

The objects and services can be discovered through various approaches [52]. SIoT establishes social network among objects and receives information from these objects on the network for locating objects/services. This subsection presents the different discovery methods and their classifications based on objects contextual information. Fig. 5 illustrates the classification.

3.3.1. Extrinsic or objective aspect

Based on the physical aspects of the objects surrounding environment, discovery systems are categorized as follows:

(i) *Location based Discovery :* discovers the services by establishing a spatial social structure among objects based on absolute or relative location to other object. For instance, locate a baggage drop-off point by establishing a social network at the airport .

(ii) *Time based Discovery:* discovers the services by establishing a temporal social structure among objects, based on the information produced at the specific period or time. For instance, find the number of passengers who are presently boarding so that the passenger can target the less crowded boarding time at the airport by establishing a social network at specific time or period.

(iii) *SpatioTemporal based Discovery:* discovers the services by establishing a spatio-temporal social structure among objects, based on the events that are monitored at the location and the time at which the event was triggered. For instance, search the coffee shop nearest to my location, which opens at 11 pm today.

(iv) *Event based Discovery:* discovers the services by establishing social relationship among objects based on events that take place in the real-world. For instance, provide information to users that they might be interested in like *train is delayed* by tracing users regular movement trajectories on smart phone.

3.3.2. Intrinsic or subjective aspect

Based on the internal sociality feature of the objects such as preferences, situational needs, long-term social relationships etc. discovery systems are categorized as follows:

(i) *Encounter History based Discovery:* discovers the objects using the long-term social relationships that exists between objects i.e., the objects that have frequently encountered or met in the past.

(ii) *Mobility Pattern based Discovery:* applies trajectories of the mobile users with similar behaviour and movement patterns in object search.

(iii) *Encounter History and Mobility Pattern based Discovery:* utilizes both encounter history and movement patterns of users to search objects.

Algorithm 2 outlines the steps for service/object search in a subjective context.

Algorithm 2: Steps for Object/Service Search in Subjective Context

Input: Requested Service List from the User
Output: Result set with matching objects
Step 1 : Pattern Extraction.
foreach *objects in SIoT* **do**
  1. Extract encounter frequency of objects with similar interest.
  2. Extract the trajectories of the mobile user with similar behaviour and movement patterns.
end
Step 2 : Construct community based on the extracted patterns.
Step 3 : foreach *service in the RequestedList* **do**
  if *object in the community matches the service request* **then**
    add the object to the result set
  end
end
Step 4: Return the result set.

3.4. Design strategies

This subsection presents the design strategies to be considered for service discovery process in SIoT system.

3.4.1. Communication topology

Service Discovery in IoT follows three different communication topologies.

(i) *Centralized:* A centralized network of objects considers that all objects are connected to a centralized entity, which acts as a directory and handles the request from all the objects.

(ii) *Distributed:* In a distributed network there is no centralized entity and each object creates various types of relationships to navigate the network for service and object discovery.

(iii) *Hierarchical:* In a hierarchical network, objects are connected to control objects which maintain partial directories; discovery is performed by sending a request message between the control objects.

3.4.2. Structuring discovery area

Typical feature of the discovery area in SIoT system determines the type of the discovery algorithm employed. The discovery area is constructed using the following design strategies:

(i) *Caching:* The information collected from the discovery area in the SIoT network is cached by the intermediate objects to distribute the information and offer it to the other requests in the network [53].

(ii) *Indexing:* The information captured from the discovery area in the SIoT network is collected and indexed for effective and quick lookups at the middleware. Indexer uses features like context data.

(iii) *Crawling:* Crawler maintains the information about discovery space visiting every object in the SIoT network. When an object receives a new request, initially it enquires if any of its friends afford to provide the service, otherwise the graph of friendships is crawled to fetch the services.

(iv) *Ranking:* The relevant service that matches the query request is determined by ranking the services based on rating, trust etc. adopting several approaches as described in [54].

3.5. A review of existing discovery schemes

This subsection presents the review of existing service discovery approaches based on the classification of discovery techniques discussed in the previous subsection.

3.5.1. Location based discovery

Objects are discovered based on the absolute location, refers to a fixed point on the earth's surface expressed by a coordinate system such as latitude and longitude, or relative locations refers to location based on its proximity to some other object.

Wang et al., [55] presented a data retrieval system named *Snoogle*, designed with the lower price wireless sensor networks for the physical world. *Snoogle* works as a search portal allowing individuals to discover physical things in their surroundings. It uses information retrieval methods to process user queries and to index information, and Bloom filters to minimize the communication expenses. It is additionally devised with security and privacy protection to safeguard confidential information. Tan et al., [56] introduced *Microsearch*, which is ideal for embedded devices in the pervasive computing environment. It provides a system architecture that efficiently uses resources to index and store different inputs. They use space-saving algorithm along with Informational Retrieval scoring and returns the *top-k* responses to a user query. These search engines cannot appropriately scale to the increasing number of queries or/and devices since they are built on a centralized framework.

Jara et al., [57] sketches an architecture called *digcovery* for large-scale service discovery using location. It facilitates the communication with IoT and offers a compatible and appropriate mechanism for global discovery of smart objects and sensors in various instances. The architecture focuses on enhancing the efficiency and sustainability of deployments, permitting individuals to sign up or include their personal devices to access or discover them from anywhere through smart phones. The drawback is that it relies on a centralized service, subjecting search portal to set up the assimilation of dispersed service directory sites.

Li et al., [58] proposed a decentralized location-preserving context-aware approaches for discovering services in IoT. The framework adopts semantic web techniques, specifically ontology to encrypt the context information and selects the best suitable services. Ontology gives a basic knowledge of the context, and it allows the discovery service to derive the relationships between entities and context. The discovery structure is developed on a distributed peer-to-peer (P2P) architecture that is scalable and robust. It does not address asynchronous discovery operations, that are specifically important in context-aware systems.

3.5.2. Event based discovery

Objects/ services are discovered based on the usage events of the IoT objects or on the events that takes place in the real world.

Yachir et al., [59] have designed a service-oriented, event-aware, and user-centred framework to efficiently carrying out service monitoring and to automatically handle activities that appear in the ambient environments. The service monitoring boost self-adaptation to sudden revisions and guarantees continuity of good quality services. The recommended framework has been executed and verified with an instance committed to every day task recognition in an Ambient-Assisted Living (AAL) atmosphere and thus enhances the efficiency in case of large scale environment. It does not address the performance of the services and event monitoring strategy for different preconfigured parameters such as ambient service class statistic, detected events statistic *etc.*

Hussein et al., [60] designed an adaptive service platform architecture for providing services in SIoT environment, based on the cognitive context-awareness computing. Contextual information presented in the instances of Social IoT are of two types: the subjective and the objective context. The subjective context expresses the humanistic and sociable aspects such as feelings, desires, trusted services, associations, *etc.* while the objective context exhibits the physical components of the users neighbouring atmosphere such as time, location, device condition, accessible services, *etc.*

Hussein et al., [61] extended a dynamic and goal-based social framework, namely Dynamic Social Structure of Things (DSSoT). It is designed to enhance sociality and to narrow down contextual complexity to situational-awareness for heterogeneous Cyber Physical Social Systems (CPSS). Dynamic service discovery framework to embed intelligence in the SIoT environment using a cognitive reasoning mechanism is proposed in [62]. The framework addresses the intelligence and context-awareness along with the user-friendliness and connectivity for improving the smart service discovery and adaptability to individuals requirements and consequently, it strengthens users experience in smart spaces. It demonstrates the implementation of dynamic smart service discovery in the real life setting considering just one instance i.e., an airport terminal instance, however they have not extended to other instances of smart places.

Jung et al., [63] proposed a smart object discovery mechanism choosing hypergraph based overlay network model. It adapts to the dynamic feature of the IoT objects and relationships. It separates the search space into three abstraction layers: task, interface and interaction layers to simplify the management of IoT objects and their relationships. Additionally, the partition of the search space increases the speed of the overall search process. Thus, the proposed object discovery technique manages to locate the most ideal object that meet the user requirements and fairly endure with the heterogeneous IoT objects.

To understand the proactive discovery of the future Internet, Yao et al., [64] modelled various interactions of IoT objects and delivered the most appropriate things to individuals based on their interests and preferences. The hypergraphs are used to discover a relevant thing from the usage histories of objects. Further, various kinds of relationships between several actors and a ranking approach is suggested for recommending the most appropriate IoT objects.

Yao et al., [65,66] have proposed a unified probabilistic matrix factorization based framework to recommend the most suitable thing to use at the specified time by exploring user–thing, user–user, and thing–thing relations. It outperforms the conventional graph based method by achieving a high correlation and significantly improves the accuracy in recommendations. However, the delay is large and it is not feasible for exploring IoT objects in real-world applications. Moreover, the approach cannot capture the dynamic nature of objects and its relationship, which is one of the most required features of IoT.

3.5.3. Interest similarity and encounter history based discovery

Objects are discovered based on interest similarity among users or the frequency of social interaction between objects.

Han et al., [67] studied the features that correlates the users interest to improve the social based services such as friend prediction and recommendation using three kinds of users details: demographic information, social relations and users interest. It observed that people who possess identical demographic qualities show resemblance according to their interest areas such as music, film, and TV. As a result, it indicates that the interest similarity of an individual is associated with several social profiles like age, gender and geographical space. It also discloses that on any interest domains, friends are expected to possess similar interests. Accordingly, it reveals that different social characteristics are interrelated to users with similar interests having different impacts.

Yang et al., [68] designed a joint friendship interest propagation model that combines the friendship and interest structures, enabling users to predict both the objects of potential interest and various other users with the same interests. The model chooses information from user–object communication and user–user relationship and builds the recommender systems by integrating users' social network details in each trust network and friend network .

Qiao et al., [69] proposed a friend recommendation system mining the users check-in behaviour in the real world. It analyses the spatiotemporal characteristics of an individual and applies Encounter probability to measure the behaviour correlation of two unfamiliar people based on their check-in histories. It is proved that users of similar interest visit the same spot at the same time slice more often and can be recommended as friends. Thus, the interest similarity among users can classify the identical neighbours for the requested user and discover the target resource.

Shen et al., [70] proposed the peer assisted video clip posting system, named SocialTube. It describes the interest collection communities named as swarm, and posted the video chunks in every swarm that possesses a higher possibility of having the targeted video clip. As a result, it minimizes the rising expenses of web server storing space and larger size of query flooding. They even identified that the majority of users based on their interests possess identical viewing patterns. Thus, the SocialTube permits the user to discover the intended resources easily within the swarm ensuring the navigability and cost efficiency. Similarly, when every object of Social IoT possesses identical pattern for the desired resources, it can be categorized to repeatedly yield target resource [71].

Chen et al., [72] described a peer-to-peer social network based content file sharing method for disconnected mobile ad hoc networks. The system utilizes interest extraction criteria to obtain nodes interests offered by its own files for content driven file browsing. It combines nodes with similar interest that often meet one another as neighbours for effective file search. The nodes are classified based on the movement into two kinds namely stable nodes and highly mobile nodes. Stable nodes frequently interact with the same community members and are generally selected as community coordinator for intra-community communication whereas highly mobile nodes interact with the other communities and are appointed as brokers for inter-community browsing. Thus interest based similarity can successfully discover the required resources [73,74].

Kang et al., [75] proposed the Social Correlation Group (SCG) to locate the target resource in SIoT environment. The SCG includes extremely related neighbouring nodes, obtained on computing the social correlation between an individual and each neighbour. The correlation value shows the way the nodes are related and extremely correlative neighbours are used to discover the required resources. It also provides the characteristic to design, adjust and upgrade the SCG and build a wide range of Social Correlation Groups to minimize the discovery time and traffic costs. However, the SCG performance have not been analysed by aggregating the devices profile like owner, type and geographical location.

Li et al., [76] have developed a resource discovery algorithm for disconnected and delay-tolerant Social IoT. The recommended algorithm is based on the similarity of the nodes preference and movement pattern and includes the 3-D geographical locality interest to increase the effectiveness of search to limit the system overlays for SIoT settings. It is analysed in an opportunistic Social IoT environment and outperforms the traditional discovery scheme in regards to average delay and search efficiency. The limitation is that, they do not use the characteristic of daily social behaviour of human to develop an efficient prediction system.

Chen et al. [77] improved the web service discovery primarily emphasizing on the fulfilment of web service quality by considering the social correlation between service modules. When it comes to an IoT service, various criteria apart from quality need to be looked into, like the locality of the services and the association between two services. To evaluate whether a service is satisfactory or not, it is not ideal to use only the quality factor.

Misra et al., [78] proposed a community detection algorithm for the combined network of IoT and social network. To handle the problems in the complex structure of IoT and Social network, it employs a graph mining concept in which the nodes in complex networks are separated as basic nodes and IoT nodes. It specifies that two nodes are claimed to a part of community, only if the nodes are in the range of one hop and have a minimal of two common friends. A node may be a part of various communities, and it functions effectively for weighted graphs. The approach is not generalized to all networks; it is based on social networks such as Facebook and it cannot give results for directed networks, and it does not serve the self loops in graphs.

Li and Wu et al. [79] proposed a Mobile community-based Publish/Subscribe scheme (MOPS) that facilitates the content based service provisioning using the neighbouring connections among the nodes. It construct communities in a distributed manner by extracting the nodes encounter frequencies. The Publish/Subscribe scheme determines the interface called the push–pull boundary by integrating the push and pull strategies and deploys brokers to link the boundary. The brokers propagate and accumulate events by utilizing a unique weighted scheme. The performance of the MOPS is presented by substantial real and synthetic trace based simulation results. Bhaumik et al., [51] devised a method to reduce search space for the huge amount of data generated from sensors by using ownership information of sensor in the social network based on their common interest and associations.

3.5.4. Mobility pattern based discovery

Mobility pattern based approach applies trajectories of the mobile users with similar behaviour and movement patterns for object discovery.

Shen et al., [80] have addressed the issue of expansively deployed RFID devices and the centralized search, by implementing a social-aware distributed cyber–physical human-centric search engine. The system locates objects held by users based on the regular movement patterns and predict the users locations during unusual events using a social-aware Bayesian network. However, it fails to address user behaviour for a specific action.

Jian et al., [81] have developed a cognition algorithm to check out the behaviour of the movable nodes by analysing the social characteristics. The algorithm explains the social relationship of the nodes and extracts the parameters like distance and interaction factor by quantifying the social relationship. The typical theory of social networks has been applied to study the behaviour of the movable nodes. It only considers one-to-one communication i.e., the communication between persons and objects and lacks the instances that one person possesses several objects and where objects are static.

You et al. [82] proposed a mobility pattern based optimal routing algorithm utilizing a local [83] and tabu-search [84] scheme for social delay tolerant networks, that consists of mobile nodes with social characteristics. The tabu-search based routing guides the relay node sets in evolving the optical node set for the destination node. The mobile-aware nodes in target region are selected by analysing their social relations and by mining activity rules and community property of the nodes. It efficiently discovers the nodes and improves the success ratio of service discovery.

Girolami et al., [85] proposed a proactive service discovery procedure for MANETs that utilize both social behaviour and human mobility. The protocol is based on the idea that the efficiency of service discovery is highly impacted by the users behaviour with time and by their mobility. In fact, people with similar interests generally have interactions with each other, therefore they may be interested on the same services. The protocol obtains an enhanced performance while finding the services. Thus mobility pattern based approaches experience reduced delay in resource detection and transmission compared to the social interaction based approach. The performance level of the resource detection is reduced since they do not completely utilize the user preferences.

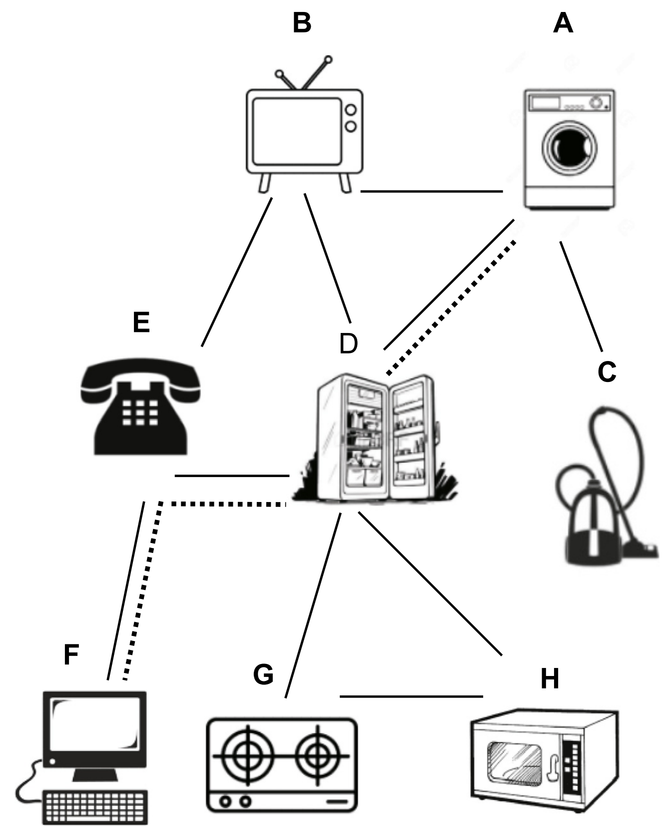

Fig. 6. Distributed object discovery in a smart home.

3.6. Service composition

Service Composition enables the interactions between objects where the services are identified by the service discovery component. To facilitate the demanding request of services, service composition component composites series of feasible IoT services and establishes social relationships between IoT services.

Chen et al., [86] have proposed a distributed social structure based technique for IoTs service composition and object management. It encapsulates IoT devices from heterogeneous networks using web services such as RESTful and a 3-D social structural design that is employed to illustrate the relationships among objects. In every aspect of social network, they developed data structures along with algorithms, and run the algorithms parallelling for service selection and service discovery. In addition, the proposed service composition scheme can set up IoT objects collaboration and complex functions execution. It provides an effective technique for IoTs object management and service composition.

As seen in the research studies detailed above, the social side of IoT provides more effective and efficient discovery of services. Table 5 provides a summary of evaluations for different service discovery techniques based on the metrics described in the previous subsection.

4. Network navigability and relationship management

4.1. An overview of network navigability

A network is navigable if and only if there is a shortest path between all or almost all pairs of objects in the network [87]. At present, the number of smart objects getting connected to the IoT is increasing and thus the relationship and accessibility timeframe for the service search has also increased. Social IoT offers a solution for easy access of such

Table 5
Summary of reviewed research publications: Service discovery.

Research publication	Discovery techniques	Data model	Design prin.	Comm. topology	Relationship	Dataset	Implementation
Hussein et al., [62]	Location and Event based	SIoT ontology [88]	Indexing	–	Social Structure Relationships	Synthetic Context Dataset generated by characterizing users situations in smart airport.	Mobile Application
Li et al., [76]	Spatio temporal Encounter History based	Community Construction	Crawling	Distributed	Preferences and Movement pattern	Data collected from the mobile social activities of the users based on the campus environment of Jiangsu University in China.	Opportunistic Network Environment (ONE) simulator
Shen et al., [80]	Mobility Pattern based	Distributed Hash Table	Indexing	Distributed	Users Regular movement pattern and their behaviour	Reality Mining Data on human mobility — MIT Dataset [89]	PlanetSim Simulator
Jung et al., [63]	Objects Usage Events and SpatioTemporal based	Hypergraph based network model	Search Space Partition	Centralized	Inter-object Social Relationships	Washington State University's CASAS Dataset [90]	Smart Home Automation Demo Box using various Sensors and Actuators
Kang et al., [75]	Interest Similarity based	Social Correlation Group (SCG)	–	Distributed	Social correlation ship	Facebook dataset provided by the Stanford Network Analysis Platform (SNAP) [91]	Simulation
Deng et al., [92]	Event based	Correlation Graph	Indexing	Centralized	Correlated Event Relationships	User Analysis Dataset	Desktop Search Engine
Bhaumik et al., [51]	Interest Similarity based	Social Network Graph	Crawling	Centralized	IoT Object and User Association	–	Ride-Sharing/Car Pooling Application
Wu et al., [93]	Event based	KeyGraph Structure [94]	Crawling and Caching	Peer-to-Peer (P2P)	User and IoT Object Relationship	Open Source Vulnerability Database (OSVDB) [95]	Matlab Simulation
Yachir et al., [59]	Event based	Service invocation model	Indexing	Centralized	subscription/ notification mechanism	Ambient-assisted living environment	real environment
Sunthonlap et al., [96]	DepthFirst Search strategy	Communication network and the Overlay Device Social Network	Ranking and Crawling	Social-Aware and Distributed	Friendship	Random Network and a Scale-free Network	Simulation
Luis-Ferreira et al., [97]	Event based	Databank of Human Emotions and Sensations	Indexing	Centralized	IoT Object and User Relationship	–	–
You *et al.* [82]	Mobility Pattern based	Local search algorithm [83] and the Tabu search algorithm [84]	Crawling	Social-Aware and Distributed	Users Movement patterns of commonly visited location	Working Day Movement Model (WDMM) [98]	ONE simulator [99]
Yang et al., [68]	Interest Similarity based	Friendship and Interest Correlation model	Crawling and Ranking	Distributed	Friendship Network Graph (user–user friendship, user-application interest network)	Yahoo! Pulse Data	Simulation
Shen et al., [70]	Interest Similarity based	Clustering	Crawling and Ranking	Peer-to-Peer (P2P)	Social relationship, interest similarity, and physical location	Facebook video trace	Simulation
Girolami et al., [85]	Mobility Pattern based	Community Construction	Crawling	Social behaviour and Distributed	User Movement and behaviour along time	Human Community-based Mobility Model (HCMM) [100]	Simulation
Li et al., [58]	Location and Context based	Context Ontological model	Indexing	Distributed	Semantic matching	Georgia Tech Internetwork Topology Models (GT-ITM) [101]	Simulation

(*continued on next page*)

Table 5 (*continued*).

Research publication	Discovery techniques	Data model	Design prin.	Comm. topology	Relationship	Dataset	Implementation
Yao et al., [66]	Context based	Hypergraph based model	Indexing	Distributed	Objects Usage and Objects Correlation	Washington State University's CASAS datasets [90]	Simulation
Han et al., [67]	Interest Similarity	Distribution of Interest	Indexing, Ranking	Distributed	Social Relations, Demographic Information, Users Interests	Facebook social network dataset	Simulation
Qiao et al., [69]	Spatio temporal Interest Similarity based	Encounter Probability model	Ranking	Distributed	Used Similar check-in behaviours	Gowalla dataset [102] from the Stanford University	Simulation
Chen et al., [72]	Social Contact based	Community based mobility model	Indexing	Peer-to-Peer (P2P)	Long-term Neighbouring Relationship	Haggle trace [103] and MIT Reality trace [89]	NS2 Simulation
Chen et al., [77]	Social interaction based	Social link model	Crawling	Distributed	Social Relationship among related services	Global social service	Simulation
Li and Wu *et al.* [79]	Encounter History based	Community mobility model	Indexing	Distributed	Nearest Neighbouring Objects frequency of contacts	Synthetic mobility traces from Florida Atlantic University (FAU) buildings	Simulation
Misra et al., [78]	Interest Similarity based	Graphical model	Crawling	Distributed	Social Community	Social Network such as Facebook, Google+	Simulation

devices with the use of social network. The SIoT structure is based on the strategy that each object utilizes its friendships, explores its neighbours and the friends of its neighbours in a dispersed fashion, to find the preferable, reliable and scalable detection of things and services adopting the similar ideas that describe the social networks of humans. Social IoT permits the objects to discover the service by navigating through the social network of friends.

Fig. 6 illustrates an overlay of SIoT network, where friendship ties are represented as links while the best route for object A to reach the service provider is denoted as dotted line. The refrigerator (D), the washing machine (A) and the Television (B) establishes *POR* since they are built by the same manufacturer, *e.g., Philips*. The *CLOR* relationship exists between the vacuum cleaner (C) and the washing machine (A), both of which reside in the same storage room. *CWOR* exists between The refrigerator (D), the microwave (H) and the cooktop (G) that work together to prepare meals. *SOR* exists between the telephone (E) and the Television (B), and the refrigerator (D) and the Desktop Computer (F), which interact very frequently to serve the home owner. When object A needs a particular service, it uses its own friendships in a decentralized manner for service search, instead of sending a request to a centralized search engine. Using Objects friendship, the distance between service requester and provider is shortened *i.e.,* reaches the provider with small number of hops in the network, thus limiting the use of resources required for discovery operation. Algorithm 3 outlines the network link selection procedure to choose the right neighbouring object to benefit the overall network navigability in SIoT System.

Algorithm 3: Network Link Selection Process

1. *Social Structure Creation:* Objects autonomously establish friendship link with the other nearby objects and creates a social structure of objects. These friendship links are used to navigate the network, searching for requested objects/services in a distributed manner.
2. *Link Selection:* The next hop to the request is chosen based on Object Friendships and Object Similarity properties

4.2. Network link selection strategy

This subsection presents the fundamental strategy to select the network link, where the discovery request is to be forwarded. Fig. 7 outlines our taxonomy for classification of different network link selection strategies. The next hop to the discovery request is selected based on two properties:

4.2.1. Object friendship

This is intrinsic to the network and expresses the objects connectivity to the rest of the network and is determined by the following factors:

(i) *Objects Degree:* The degree of an object is defined as the number of social links associated with it. For instance, Object D has a degree of 5 in Fig. 6.

(ii) *Social Relationship Diversity:* Social relationship diversity is defined as the number of types of social links an object is associated with. For instance, object D has a diversity of 3 since it has three different types of social relationships which are *POR* (i.e., links with A and B), *CWOR* (i.e., links with G and H) and *SOR* (i.e., link with E) in Fig. 6.

(iii) *Local Clustering Coefficient:* The local clustering coefficient of an object is defined as the number of the social links among the neighbours divided by the total number of neighbours of an object. For a given object n, the local clustering coefficient CC_n is calculated as:

$$CC_n = \frac{2 * N_n}{K_n * (K_n - 1)} \tag{1}$$

where N_n represents the number of links between neighbours of an object v and K_n is the total number of neighbours/degree of object v.
For instance, object D has K_n of 5, N_n of 3 and local clustering coefficient of 0.3. The clustering coefficient measures how close an object and its neighbours form a clique [104].

(iv) *Objects Betweenness Centrality:* Betweenness Centrality of an object is defined as the number of shortest path travelled across the given object divided by the total number of possible shortest paths [105]. For a given object n, the betweenness centrality BC_n is calculated as:

$$BC_n = \frac{\rho_{uv}(n)}{\rho_{uv}} \tag{2}$$

where ρ_{uv} is the total number of possible shortest paths between object u and v and $\rho_{uv}(n)$ is the total number of shortest paths between u and v that pass through object n.
For instance, for discovery request from object A to E the betweenness centrality for object D is 2.

(v) *Objects Closeness Centrality:* Closeness Centrality of an object is defined as the average of the shortest path among the object and all other objects in the network. For a given object n, the closeness centrality CC_n is calculated as:

$$CC(o_i) = \frac{N}{\sum_{j \neq i}^{N} g(o_i, o_j)} \tag{3}$$

Where N is the total number of objects in the network and $g(o_i, o_j)$ is the geodesic distance between object o_i and o_j. For instance, Objects *B, C* and D has a closeness centrality of 8/11, 8/18 and 8/9 respectively in Fig. 6.

4.2.2. Object similarity

This is an external property with respect to the network characteristics which defines the similarity between objects and the discovery request, based on two factors:

(i) *Co-presence Duration of Object:* The duration during which the objects are near or overlapped to each other.

(ii) *Contacts between Object:* Number of times the social objects have encountered each another.

Based on the properties described above, the discovery request can quickly reach the desired target objects contacting only a limited number of intermediate objects.

4.3. A review of existing network navigability schemes

In the past, there are several independent research works that describe the conditions for network navigability [106,107].

This subsection presents the review of various research activities that are carried out to efficiently identify the strategy, for an object to choose an appropriate friend to improve the overall network navigability.

4.3.1. Object friendship

It uses internal characteristics of the network such as degree, diversity, clustering coefficient, betweenness centrality and closeness centrality of an object to navigate in the SIoT network.

Nitti et al., [108] have determined the navigability characteristics of the SIoT network where the nodes are connected as friends and every

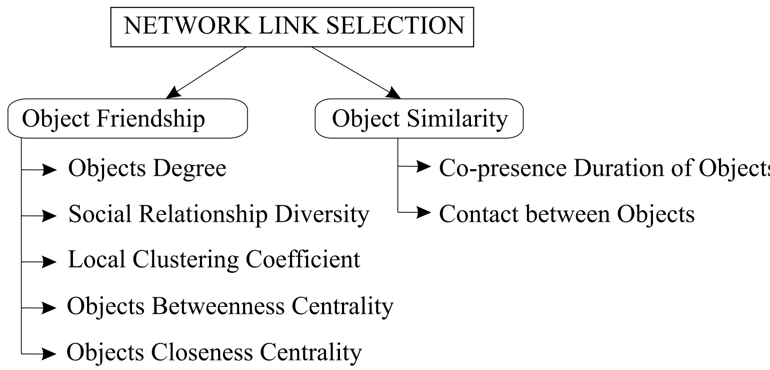

Fig. 7. Taxonomy for SIoT based network link selection schemes.

node in the network has information about the neighbouring nodes and uses that to pick friends and navigate the network globally. Five heuristics are described to select an appropriate link in the network and analysed the performance of the network in terms of local cluster coefficient, average degree, average path length and giant component. Nitti et al., [19] proposed feasible heuristics based on the local network properties which should be implemented by every node in the network when adding new friends. Further, Nitti and Atzori [109] figured out the possible solutions to minimize the distance between service requester and service provider in the SIoT instance by recommending two approaches, namely a caching system and friendship selection mechanism. In caching system, objects save information for friendship selection mechanism and for future request. It enables the objects to set up a new friendship in the direction the information is disseminated by the service provider. But the suggested techniques are extremely basic and the efficiency has been evaluated in terms of global [108] and local [19] network navigability and object search is carried out with the use of conventional graph structures and therefore they cannot capture the dynamicity of IoT objects.

Militano et al., [110] proposed a distributed friendship selection approach based on a game theoretic model using the Shapely-value based algorithm. It aims to define a strategy to select friends that is efficient, distributed and dynamic. Further in [111] a utility feature such as average local clustering coefficient [104] and group degree centrality [112] for the objects is suggested, which improves the performance by reducing the computational complexity and ensures convergence. Although, the objects social structure, offers network navigability and ensures effective object and service discovery, there is a need to focus on a large amount of contextual data over scalability and complexity challenges on data gathering and processing.

Girau [113] proposed neighbour discovery algorithms for establishing a new relationship between objects in SIoT. One of the algorithms relies on the radio channel scanning, whereas the other two algorithms use the localization feature exploiting the already existing objects social network for neighbour discovery. The limitation is that, the algorithms has not been evaluated in real scenarios.

Zhu et al., [114] proposed a privacy preserving interest based forwarding scheme for social internet of vehicles which protects the sensitive interest information and improves the forwarding performance of the mobile vehicles. Lin et al., [115] have developed the social vehicle route selection algorithm to analyse the traffic situation and to reduce the traffic congestion. Initially, vehicles are divided into various clusters based on the current and past driving information and then determines the optimal route using game evolution. However, to facilitate online data processing for massive data algorithms based on artificial intelligence must be designed.

Mardini et al., [116] proposed a friendship link selection strategy using genetic algorithm to find a specific service in the SIoT environment. It improves the network performance in terms of average path length, average cluster coefficient, and average degree.

4.3.2. Object similarity

It uses the external characteristics of the network such as similarity between objects such as co-presence duration and contacts between objects. Nitti et al., [117] proposed a SIoT based decentralized object discovery algorithm to provide a specific application services. The Social IoT establishes a friendship links between objects and creates a social structure of objects. Every time, an object receives a new query, it finds out if anyone of its friends has the ability to execute them, or else it chooses within them the one that possesses the greater chance to fix the query. The proposed criteria selects the next hop to query based on two properties namely degree of centrality i.e., intrinsic and object similarity i.e., external. One which is intrinsic to the network is based on objects companionships, and the one that is external considers the resemblance among the objects and the query requirement. However, the object discovery algorithm does not consider semantic distance among the services. Asl et al., [118] exploits interactions among objects such as the co-presence instances (i.e., the moment the objects are near to each other) and the number of contacts between objects to search socially similar smart objects in SIoT network.

Table 6 provides a summary of reviewed research publications for network navigability based on the metrics described in the previous subsection.

4.4. Relationship management

Relationship management component embeds the intelligence into the objects to ensure that they realize friends and foes and initiate a friendship, update the status as and when changes occur and terminate the relationship.

Atzori et al., [5] observed that intelligence is a substantial part of the SIoT paradigm and it is essential for establishing, upgrading, and aborting the objects relationship in SIoT. The current IoT does not have sufficient intelligence and cannot reach the predicted increase in the applications' performance. To integrate intelligent thought into IoT, Zhang et al., [123] introduced a novel concept of Cognitive Internet of Things (CIoT). CIoT integrates IoT with cognitive and cooperative mechanisms to achieve intelligence and promote performance in the IoT systems. Existing research study on IoT, targets at enabling the objects to observe, listen, and sense the physical world on their own and maintain connectivity between them to share their observations. Just connection between the objects is insufficient, the objects must develop the capability to discover, believe, and realize the social and the physical world on their own.

Wu et al., [124] developed a framework for the CIoT, by considering the requirements of a social network. The framework consists of three layers: the physical, cyber and social world. Further, the cyber world includes (i) the sensing management layer, where the contextual information are accumulated (ii) the data-semantic-knowledge layer, where the sensed information are converted into relevant semantic information (iii) the decision making layer, where the knowledge that

Table 6
Summary of reviewed research publications: Network navigability.

Research publication	Friendship selection model	Design principles	Network link selection	Dataset	Implementation
Nitti et al., [108]	Social Relationship Graph	Crawling	Local Clustering Coefficient and Objects Degree of Centrality	Brightkite from Stanford Large Network Dataset Collection [119] (Objects Enclosed between Atlanta and Boston Region)	Gephi visualization Software [120]
Militano et al., [111]	Game Theoretic and Shapley-value based Model	Crawling	Average Local Clustering and Group Degree Centrality	Brightkite from Stanford Large Network Dataset Collection [119]	Matlab Simulation
Nitti et al., [117]	Social Relationship Graph	Crawling	Object Friendships and Similarity property	Brightkite from Stanford Large Network Dataset Collection [119] (Objects Enclosed between Atlanta and Boston Region)	Matlab Simulation
Zhu et al., [114]	Interest-based Communication	Social-based Data Forwarding	Objects Common Interests	Mobility Trace Datasets	Opportunistic Network Environment (ONE) Simulator
Lin et al., [115]	Game Evolution	Crawling	Historical and Current Social Correlation between Vehicles	Historical Dataset of Vehicles in a city of USA with the Map Information of openstreetmap (OSM)	Java Simulation
Nitti et al., [109]	Caching and Friendship Selection Models	Caching and Crawling	Objects Degree Centrality and Betweenness Centrality	Brightkite from Stanford Large Network Dataset Collection [119] (Objects Enclosed between Atlanta and Boston Region)	Matlab Simulation
Mardini et al., [116]	Genetic Algorithm	Crawling	Average Degree and Average Cluster Coefficient	Brightkite from Stanford Large Network Dataset Collection [119]	Gephi visualization Software [120]
Asl et al., [118]	Social interaction graph	Crawling	Co-presence instances and Number of contacts	Cambridge dataset [121]	SWIM simulator [122]

is derived in the prior layers is transferred to the intelligent agents for decision making, and (iv) the service evaluation layer, where the given services are reviewed by people and agents.

CIoT has the feature to link the physical world and the social world and thus improves the smart resource allotment, smart service provisioning and automatic network operation. Kasnesis et al., [48] proposed a cognitive middleware that handles the social relationships of smart Internet of Everything (IoE) entities in the SIoT paradigm. They address the interoperability challenges regarding to service discovery to support the smart entities collaboration for achieving a common goal. An appropriate solution for basic necessities of SIoT, such as scalability is not considered.

Zhang et al., [125] proposed a Sociology based interaction relationship model by analysing the social features of IoT objects. It uses a combination of four major relations such as the Communal Sharing relationship, the Equality Matching relationship, the Authority Ranking relationship and the Market Pricing relationship for every interaction relations among IoT objects. Further, along with a straightforward automated relationship awareness, service enhances the intelligence of objects, it minimizes the IoTs dependency on human intervention and makes the objects in IoT smarter.

Console et al., [126] have implemented intelligence as a middleware by integrating several technologies like ontology's recommendation techniques and methods for refining the users generated content. The middleware is a smart mobile application in food domain named as *wantEat*.

Through wantEat middleware, it is easy to create social relationships with users and other objects, make day-to-day objects intelligent and set objects to interact with users.

Turcu [127] introduced a cognitive robotic design relied on RFID technologies associated with IoTs and provides a social perception for objects interaction. Social networks is chosen for saving and for providing connections to the interested resources for the robot–robot and human–robot communications. The suggested design enables the expansion of the Internet of Things social ability from neighbourhood to worldwide range by combining social web details and local devices.

Li et al., [45] examined the social attributes of object such as social relationship and social existence between objects during interaction. The relationships of objects are modelled using ontology based approach and described the complex relations between objects using hypergraph architecture [128]. Jung et al., [129] have proposed a prediction model that infers the social relationship between objects and gauge their corresponding social strength capturing the spatiotemporal characteristics and diversity of the objects co-usage data. Gui et al., [130] have proposed a cognitive model to depict the spatio-temporal feature of social relations of the mobile objects. The uncertainty and complexity of social relationships are determined by extracting multiple factors such as location factor that reflects the trajectory information, interaction factor indicates the encounter frequency, service evaluation interprets service historical records, and feedback aggregation indicates the collection of set of feedbacks of mobile objects. The changes of relations among objects are predicted through genetic algorithm with support vector machine (GA-SVM), the information entropy and mathematical modelling [131]. However, the model does not have a mobile-aware service center to accomplish real-time access to information.

5. Trustworthiness management

5.1. An overview of trust management

This section presents the basic definition and the concepts of trust management system. Trust is a measure of faith, confidence and expectation on the integrity, stability, honesty, safety, and other qualities of an individual. Trust is strongly associated with security because assuring user security and system security is an essential requirement to achieve trust. Nevertheless, trust is beyond security that associates not solely the security, but additionally several other aspects, like kindness, stability, dependability, availability, capability, and many other qualities of a thing.

The principle of trust is researched in various disciplines starting from psychology, sociology, philosophy, economics and so on, to computer science with each of them providing a different explanation of

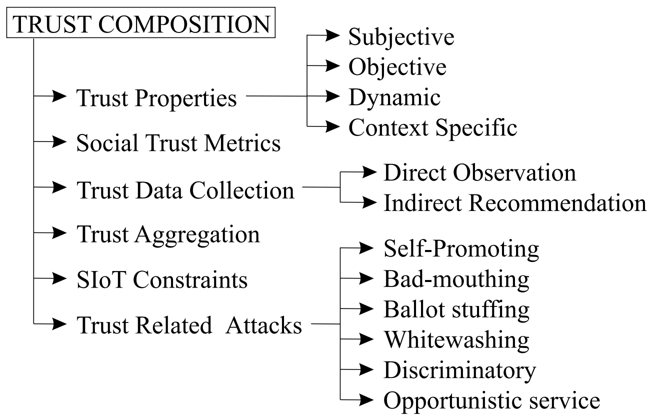

Fig. 8. Taxonomy for trust composition in SIoT.

trust. The concept of trust is originally discussed in social sciences and there are several definitions for trust.

Kini and Choobineh [132] defines trust is: *a belief that is influenced by the individuals opinion about certain critical system features.* Gradison and Sloman [133] defined trust as: *the firm belief in the competence of an entity to act dependably, securely and reliably within a specified context.* Gambetta [134] defines:*trust (or, symmetrically, distrust) is a particular level of the subjective probability with which an agent performs a particular action, both before [the trustor] can monitor such action (or independently of his capacity of ever to be able to monitor it)*. Castelfranchi and Falcone [135] defines: *Trust basically is a mental state, a complex mental attitude of an agent 'x' towards another agent 'y' about the behaviour/action 'a' relevant for the result (goal) 'g'.*

Gambetta's interpretation of trust is the one that is highly cited, where trust is considered as a threshold factor of a probabilistic distribution and only concerns those future actions that have impact on decisions. The Trust management analyses the behaviour of entities, by using their past behaviour, reputation in the network or recommendation. A reliable or a trustworthy system is required to protect against unwanted activities performed by malicious devices.

Blaze et al., [136] are the first to propose the terminology Trust Management. They recognized it as an independent aspect of safety services in network structure and defined that the trust management offers a single method for determining and analysing credentials, security policies, and relations.

Since IoT combines enormous quantity of day-to-day life objects from heterogeneous surroundings, introducing a major obstacle in safety, security and integrity control there is a need of trust management process for a SIoT system.

5.2. Trust composition

This subsection presents the fundamental components that are to be considered during trust computation for the SIoT. Fig. 8 depicts our taxonomy to classify different techniques for trust management.

5.2.1. Trust properties

Trust is computed in several ways by considering the following properties.

(i) *Subjective:* In a Subjective trust, centrality trust is evaluated using relative centrality of an object, direct service quality trust is evaluated using self-observations and indirect service quality trust is evaluated using feedbacks provided by another object.

(ii) *Objective:* In an objective trust, centrality trust is evaluated using network centrality and both direct and indirect service quality trust is evaluated using feedbacks from the other objects.

(iii) *Dynamic:* Trust assessment adaptively adjusts to the trust parameter settings in response to the changing conditions of the environment.

(iv) *Context Specific:* Trust of an object A on another object B differs from one context to another.

5.2.2. Social trust metrics

Derives the social relationship among objects and measures the social trust by connectivity, honesty, privacy, centrality *etc.* using social contact, friendship, interest similarity and community of interest.

5.2.3. Trust data collection

Data that is required to compute trust in SIoT are obtained in several ways.

(i) *Direct Observation:* An object computes the trustworthiness of another object on direct evidence, by collecting data upon interactions and observations.

(ii) *Indirect Recommendation:* Evaluates the trust on indirect evidence, by collecting data based on recommendations from the other objects.

5.2.4. Trust aggregation

Trust data collected from objects either through Direct Observations or Indirect Recommendation is aggregated using various techniques such as Weighted Sum, Fuzzy Logic, Bayesian Model, Belief Theory *etc.* [137] .

5.2.5. SIoT constraints

Trust protocols in SIoT network must support and ensure some fundamental criteria such as scalability, survivability, resiliency, and adaptability.

5.2.6. Trust related attacks

An object in SIoT network can become a threat and breaks its basic functionality. A malicious IoT object perform different trust-related attacks, itemized as follows:

(i) *Self-promoting attacks:* It publicizes its significance by providing good recommendation about itself so that it is chosen as a Service provider.

(ii) *Bad-mouthing attacks:* It ruins the prominence of a well-behaved object by disseminating bad recommendations against it so that it reduces the chance of selecting the good object as a service provider.

(iii) *Ballot stuffing attacks:* It boosts the reputation of another defective object by providing good recommendations for it so that this increases the chance of selecting the malicious object as a service provider.

(iv) *Whitewashing attacks:* It washes away its bad reputation by departing from the application and than rejoining.

(v) *Discriminatory attacks:* It selectively attack objects that do not have many common friends because of human nature or propensity towards friends in SIoT systems.

(vi) *Opportunistic service attacks:* It provides good service to gain reputation opportunistically when its reputation falls because of providing defective service.

5.3. A review of existing trust management schemes

This subsection presents the review of research publications that address the trust composition and management issues for the SIoT for a wide range of applications with different characteristics.

5.3.1. Subjective/objective based trust composition

In these type of trust composition models, the trustworthiness of a node in a SIoT network is composed using self-observation made by the observer/requester node, feedback from the peer nodes.

Nitti et al., [138,139] discussed a subjective trustworthiness model for handling trust in social and P2P networks. Every node in the network determines the trustworthiness of the other node based on the viewpoint of the common friends and on individuals experience. The trust level is analysed by applying a feedback system and by integrating the nodes reliability and centrality. An objective trustworthiness model is proposed in which each nodes information is dispersed and saved using a distributed hash table network, to ensure that every node utilize the same details. The suggested model efficiently separates every malicious node in the network . The limitation is that the trust rating makes use of only feedback information of nodes without considering information by direct monitoring. Truong et al., [140] developed a subjective based trust composition model using common interest, cooperativeness and honesty similarity social features of the SIoT components. Direct observations of the nodes along with previous encounter history is used to calculate a weighted sum through Bayesian estimation scheme. Although, several malicious attacks are handled in this work, the authors fail to consider the reputation of the nodes for service delivery and thus the system does not support recommendation feature.

Xiao et al., [141] presented a guarantor and reputation driven trust model for Social IoT environments. In the model each object is associated with a reputation rating which is saved in the object on its own and it is updated by a reputation server. Whenever an object requires a service from the guarantor, it initially identifies a guarantor for getting desired services with an agreed commission charge. The objects and gateways (nodes) make use of credit ratings to obtain services. When a node provides an appropriate service, it is given some credits as a commission. In case if it misbehaves it should pay a few credit rating to other nodes as a forfeit charge. The commission and forfeit charges acts as a guarantor for an object behaviour. Credit rating and reputation rating are the two criteria used for managing trust and discovering the malicious nodes. However, the proposed model is not tested for consistency, scalability and data managing ability in a large scale networks.

Panda et al., [142] devised a trust composition scheme based on belief network model. It makes use of transitivity and centrality scores for trustworthiness evaluation of a node in SIoT network. These scores are then subjected to a Bayesian based belief network that is augmented with a fuzzy model to compute the nearest node with highest trust score. Advantage of this scheme is that no prior interactions or social information of a node is required to compute the trust score. However, the model is dependent on the network topology and thus fails to address the dynamic scope of a SIoT network. Rafey et al., [143] presented a Context-based Social Trust model for the Internet of Things (CBSTM-IoT). The model evaluates the trust by considering the social relationships among objects it updates its trust value by recommendations and direct observations and efficiently separates the harmful nodes in the network. Disparate forms of trust like cooperativeness and different errors in the absence of malicious objects are not considered.

5.3.2. Dynamic based trust composition

These kind of trust models compute the trust assessment score based on dynamic responses of the nodes and thus are adaptable to the changing environment of the SIoT network.

Chen et al., [144] proposed an access service recommendation scheme for Social IoT environments, with malicious attacker resistance and effective service composition. A coherent recommendation metric is introduced to address critical issues such as vulnerabilities, dynamic behaviours, and resource limitations during trustworthiness analysis of SIoT services/devices. The recommendation metric integrates the social relationship among devices and timeliness properties of transactions to evaluate the service in dynamic environments. It also considers an energy aware mechanism for network security and workload balancing. The scheme prevents attacks such as Badmouthing, Ballot-stuffing and Self-promoting. The specialized remedies to SIoT constraints such as minimal storage space, scalability and computational capability have not been addressed.

Bao and Chen [145] have designed a dynamic trust protocol for IoT, based on three trust aspects namely cooperativeness, honesty, and community interest using direct monitoring and indirect referrals. It makes use of various indicators such as convergent, accurate and resilient properties to validate the trust model. The drawback is that, it did not take in to consideration certain necessities of IOT conditions like energy usage and storage management. Bao and Chen [146] aim at upgrading trust protocol recommended in [145] by reusing the similar trust measures such as honesty, cooperativeness and community interest and also considered other aspects such as scalability, adaptively and survivability to design and evaluate the protocol in the dynamic IOT environment. The trust updating is event based and the trust value computation are limited for a small collection of nodes to sustain scalability and to reduce computation time. However, a storage management technique that minimizes storage area and enhances the scalability have been proposed. The protocol has not been demonstrated for IoT operations that requires trust to reduce the hazard.

Wang et al., [147] presented a context aware trust system named CATrust, for evaluating trust in service based ad-hoc networks such as IoT network and peer-to-peer (P2P) network. It dynamically estimates trustworthiness of a service provider using the logistic regression, based on the contextual environment changes. Recommendation filtering technique is developed to investigate socially connected friends to deliver honest recommendation and to efficiently filter untrustworthy recommendations in malicious environments. CATrust outperforms in terms of accuracy and resiliency against the Internet of Things and peer-to-peer trust models. The limitation is that, it has not been validated for the real-world data. Chen et al., [148] devised and studied an adaptive trust protocol for SIoT systems. It carries out trust analysis based on users direct monitoring and indirect trust responses from different users with identical social activities. It has three metrics namely, social contact, honesty, and community of interest for refining trust responses and for evaluating social similarity. Further, a novel adaptive filtering method is designed to detect the most effective way to dynamically integrate direct and indirect trust referrals to reduce trust bias and converging time. The protocol has not been validated for properties such as convergence, precision, and resiliency for a wide range of dynamically evolving environmental problems.

Truong et al., [41] introduced a service platform that provides a trust opinion between any two entities in the Social IoT applications and services, combining three trust metrics namely Knowledge, Reputation and Recommendation. The model activates the relationships between objects, enhances the discovery of trustworthy objects by establishing a trust mechanism among objects, and improves the network performance. However, it does not address trust associated attacks and do not guarantee the scalability for the SIoT system. Guo and Chen [137] categorize trust computation methods with five design aspects such as trust formation, trust composition, trust aggregation, trust propagation and trust updation.

Chen et al., [149] have proposed an adaptive and scalable SOA-based trust protocol for IoT devices. The model selects trust feedback using distributed collaborating filtering technique from the users of IoT objects having the same social activities. It considers social relations such as friendship, social contact, and community of interest for determining the similar social interests and for refining trust feedback. It employs an adaptive filtering method for integrating indirect and direct trust toward the total trust to effectively reduce the trust assessment and convergence time. The applicability of the suggested protocol is demonstrated for a service composition application in Service Oriented Architecture driven IoT systems, in the presence and absence of service constraints. However, this technique, does not consider advanced attack behaviours such as random, insidious, and opportunistic attacks. In [150] opportunistic service attacks is considered and the resilience against these attacks is analysed. Scalability is handled by developing a smart storage management technique for capacity-limited IoT units and efficiently uses the reserved storage space. The application performance is maximized by addressing the most suitable step to integrate social similarity measurements. Other attacker behaviours such as random and insidious attacks are not considered.

Kogias et al., [151] focused on the design and implementation of an extremely scalable and Reputation Trust model for the IoTs. The model is created by combining mobile ad-hoc and peer-to-peer networks onto the IoTs concept. The model is based on the social approach introduced in the COSMOS project [25]. Each object computes the trust index of another object based on its own experiences and determines the reputation index by either referring to the COSMOS platform or by consulting its other friends. However, the suggested model has not been evaluated for the real-world instances of the COSMOS project and does not utilize the real IoT-systems to validate the scalability of the model.

Table 7 compares the trustworthiness management schemes for SIoT based on different implementation details adopted by the works.

6. SIoT platforms

SIoT platforms enables easier and reliable interaction between objects and benefits in creating new applications with the accessible object services. In this section, we review the research efforts to design and develop such platforms. We describe the research publications that address numerous challenges of cyber world by incorporating social phenomenon into the IoT domain to overcome the present drawbacks.

In recent past, several projects have aimed at the integration of the IoT into a social networking framework. In this subsection, we review the existing platforms in SIoT. Kamilaris and Pitsillides [154] implemented a smart home environment using the existing social networking infrastructure and Web APIs. The smart home setting has been established and installed in a Facebook application allowing people to create their own home network online. Even though they present a few useful ideas, the Facebook application is restricted only to the users of Facebook and just one community of objects can be created. As the interaction between objects is restricted just within each community of objects, the access to objects outside the community is certainly limited.

Deshpande et al., [155] proposed a Machine-4-Machine (M4M) theoretical model, in which social network friends can post various device features among their companions. An algorithm that enhances the degree of sharing of IoT devices by advising friendship recommendations has been presented. The execution of the model by creating an android mobile app using facebook APIs, that allows to share device features between friends have been described. However, the M4M model does not assist with complex actions of devices since it needs a co-ordination between number of devices. Makitalo et al., [156] introduced *Social Devices* that provides social–digital platform for the interaction of co-located devices and humans. The approach aims at enhancing the remote interaction for the on-line social media services whenever devices and users are discovered at the same place.

Pintus et al., [157] developed a platform *Paraimpu* for a larger range Social Web of Things. Paraimpu is a Web service platform, similar to Web services and social networks, it permits to share, use, add and interconnect HTTP enabled intelligent things and virtual things. It facilitates people to build a personalized widespread applications in a user friendly and secured way. However, none of the above mentioned work handles the heterogeneous character of devices and APIs offered by disparate manufacturers. Moreover, it did not utilize various social relationships and thereby restricts the devices and users collaboration. The platform design is further improved in [158], and explained the way Paraimpu provides a Web enabled platform with devices and services that add, adapt, compose, collect, filter, and share data from heterogeneous type of actuators and sensing units utilizing programmable panels, internet-enabled devices, services and social networks.

Girau et al., [40] described a platform for SIoT that provides a core server to execute the features such as to sign up an object, to permit the users to define the object's behaviour, to set up details regarding the objects and to establish and handle the relations among objects. The web server moves the information to the objects whenever required, for instance to activate certain service discovery. It permits even an object with minimal computing capabilities to establish and maintain its own relationships. The drawback is that, the system does not determine the trustworthiness of the received services. Beltran et al., [159] presented a semantic web service platform for SIoT using social network as a merging aspect for people, devices, and Web services. It considers Social Network as a Service Creation Environment (SCE) where users create their private services based on their devices, web services of their interest and contextual information. Web services are considered as a part of SIoT and are connected to the devices for enabling the integration of the Web with IoTs.

Byun et al., [46] proposed an ontology-based social networking platform for the IoT, named Lilliput. It uses the social relationship between people, devices, and location, and exhibits them in the form of graph. The proposed relationships are used to understand more complicated circumstances and authentication of human oriented control accessibility for IoT social network. Lilliput improves IoT social graph with increased expressivity by dealing with a service such as social interaction between smart things. The application programmers can develop IoT social network application without any awareness in both online social networks and Internet of Things. However, temporal social association between people, devices, and locations are not expressed. Zhang et al., [160] proposed an architectural design for Social Web of Thing (SWoT) platform based on social structure and the Restful Web Services. The architecture uses semantic web and translates the structural raw data into natural language, that permits devices to interact with each other and with the humans using a social network; thus, facilitating the socialization of smart objects in the web ecosystem. It also offers open Web service APIs to access the database for the third party users.

Kim et al., [47] developed a flexible framework and designed an architecture for social internet of things *Socialite*. They define a set of novel relationships for the Social IoT and discusses the possible use cases and identifies the ways to realize the use cases by associating humans and devices, and illustrates how Socialite permits them to distribute data with other people and devices. Socialite integrates numerous devices from distinct manufacturers with various types of interfaces and expresses the relationships explicitly. It achieves more effective relationship management for the SIoT by exploiting the relationship ontology and semantic rules. Atzori et al., [161] analysed the potentials of combining social networking concepts with IoT to deploy a reliable service platform. It addresses the future obstacles, of a world with a trillions of interconnected objects and highlights the major services that are emerging in the IoT field, to allow objects to enter the social loop and compare their strength and weak points by emphasizing on their technical needs and design.

Girau et al., [162] introduced a cloud based IoT platform called *Lysis* for the deployment of Internet of Things applications. The design of *Lysis* follows four major features such as social agents, Platform as a Service (PaaS) model, reusability, and cloud storage. The initial feature adopts the Social IoT principles and establishes a social relationship in an independent way for locating information and for network scalability. The major factors of Platform as a Service (Paas) are used for quick development of applications by both programmers and users. Reusability permits the developers create the templates of objects and services which is accessible to the entire community. The data produced by the devices is under the control of users that is stored at the objects owners cloud space.

Zhang et al., [163] focused on applying Object Oriented method [164] for SIoT, and specified its utilization on Android based Smart

Table 7
Summary of reviewed research publications: Trustworthiness management.

Research publications	Trust properties	Social trust metrics	Trust aggregation	Trust data collection	SIoT constraints	Resilience to malicious attacks
Nitti et al., [139]	Subjective and Objective	Feedback, Credibility and Centrality	Weighted Sum	Experience and Opinion of the Common Friends based	Scalability and Adaptability	Malicious Attacks Considered
Truong et al., [140]	Subjective and Asymmetric	Cooperativeness, Community-Interest, Honesty and Similarity	Weighted sum, Machine Learning Algorithms and Bayesian Estimation [152]	Direct Observation, Personal Experiences and Global Opinions	Resiliency	Self-Promoting, Bad Mouthing, and Ballot Stuffing
Xiao et al., [141]	Context specific	Social Cooperativeness	Probability	Reputation Rating	–	Malicious Attacks Considered
Panda et al., [142]	Subjective	Degree, Closeness and Betweenness Centrality	Bayesian Belief and Fuzzy Logic	Belief based	Scalability	–
Rafey et al., [143]	Subjective and Context Specific	Community Construction	Weighted Sum	Direct Observations and Indirect Recommendations	Scalability, Adaptability	Malicious Attacks Considered
Chen et al., [148]	Dynamic	Honesty, Cooperativeness and Community of Interest	Weighted Sum	Direct Observations and Indirect Recommendations based	Scalability, Adaptability, Resiliency	Bad Mouthing and Ballot Stuffing Attacks
Chen et al., [150]	Dynamic and Adaptive	Friendship, Social Contact, Community of Interest	Bayesian Model	Direct Interaction Experiences and Recommendations	Scalability, Adaptability and Resiliency	Bad Mouthing, Ballot Stuffing, Self Promoting Opportunistic Service Attacks
Truong et al., [41]	Dynamic	Honesty, Cooperative, Community-Interest and Experience	Fuzzy and Multi-Criteria Utility Theory	Reputation, Recommendation, and Knowledge	Scalability	Malicious Attacks Considered
Abderrahim et al., [153]	Dynamic	Community of Interest	Weighted Sum	Direct and Indirect Observations	Scalability, Adaptability, Resiliency	On–Off Attacks
Chen et al., [144]	Dynamic	Coherent Recommendation	Weighted Average	Direct and Indirect reputation	Resiliency	Badmouthing, On–off, and Intelligent Behaviour Attacks

office environment. It organizes the entity objects by identifying the relationships between nodes, class, owner and entity object, in addition to six basic attributes and three methods. Then, the smart office application named *WeChat*, uses the sensor data and sends messages to the user *via* a cloud web server on social networks. Cicirelli et al., [165] proposed a Java-based platform named *iSapiens* to design and implement the Smart Environments. It leverages the SIoT paradigm to dynamically add a new object into the Smart Environments without human intervention and deals with the interoperability and scalability issues. It exploits the edge computing paradigm to create a pervasive smart environments and manages distributed storage and computational resources without causing bandwidth shortage and minimum latency. Utilizing *iSapiens*, a general cyber–physical systems was developed for the design and implementation of smart city services and applications [166]. Shamszaman and Ali et al., [44] have proposed a user directed and object directed interaction framework adopting semantic ontology for creating a smart intelligent society. In user directed interaction, user can spread a requirement and select the suitable service or friend that matches the requirement criteria from online social network whereas in object directed interaction object itself identifies its own or owners needs cognitively and intelligently to choose the service that matches its requirement.

7. Future research directions

This section presents the future research directions to improve the overall network navigability, to efficiently implement discovery methods and to discover smart mechanism for trust evaluation in the SIoT system.

(i) *Enhanced Service Provisioning through Dynamic Social Relationships:* Atzori et al., [5] derived some basic social relationship types between objects for efficient discovery of services. However, it does not support dynamic establishment of new relationships in a network of social objects. Since, some applications with intelligent service features require dynamic object selection. Therefore, objects need to acquire the ability to infer new relationships for interconnection with other objects in the system. Ali et al., [33] utilized semantic ontology to dynamically establish a new social relationship for efficient service provisioning. Other such dynamic social relationships types should be established to achieve multicast feature, inter-connectivity and classified results.

(ii) *Optimal Link Selection Strategy:* Object discovery in SIoT is considered as a critical issue due to its large and complex discovery area. This complexity has arised from the fact that every object uses its friends or Friend of a Friend (FOAF) relationship to discover a particular service. However, this normally affect the search time because each object manages a large number of friends. Therefore, finding a near optimal solution for the link selection problem in the SIoT need to be addressed.
Mardini et al., [116] proposed a link selection approach utilizing genetic algorithm [167–169] to locate the near optimal link in the SIoT network. Such optimal link selection strategy are to be designed to achieve inter-connectivity feature.

(iii) *Construct Large Scale Social Environments/Platforms to Address Dynamicity, Scalability, Object Heterogeneity, and Openness Issues:* A Large Scale Social Environments (LSSE) is dynamic and open system that provide cyber–physical social services to users characterized by a multitude of heterogeneous interconnected IoT objects. It is a longtime running systems where new objects can be dynamically joined and detached, and a new functionalities can be added, removed or replaced by applying the existing objects or services. Cicirelli et al., [170] proposed an agent based approach for the development of Large Scale Smart Environment leveraging SIoT and edge computing paradigms to address the challenging issues such as scalability and interoperability.

(iv) *Self-Management:* SIoT is considered to be a world wide technology composed of trillions of people and objects, equipped with sensing capabilities. User need not check the status of the surrounding objects any more, it should be operated automatically at most levels and update the user with its present state.

(v) *Smart Mechanism for Trust Aggregation:* The trust weights of the objects change according to the specific context. For such adaptively changing weights, smart mechanism is required to emulate the trustor's inclination and environmental conditions to the trust aggregation evaluation model.

8. Conclusions

In the recent past, the things getting connected to the internet is exploding on an hourly basis, thus providing a social frame to the IoT down scales the visibility of the IoT and ensures the navigation between objects. The Social Internet of Things (SIoT) has been the topic of various autonomous research activity since it guarantees to obtain scalable services with trillions of interconnected objects and supports novel interesting applications. This paper has reviewed the latest research studies on Social Internet of Things for discovering things that provides the desired services, for embedding intelligence into objects, for enabling the interactions between objects and for managing trustworthiness between objects to interact reliably.

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